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and the Bulletin of the Society of Economic Geologists

CONTENTS

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Vol. XL JUNE–JULY, 1945 No. 4

SALT WATER ENCROACHMENT IN LIMESTONE AT SILVER BLUFF, MIAMI, FLORIDA.

RUSSELL H. BROWN AND GARALD G. PARKER.

ABSTRACT.

Silver Bluff is part of a low coastal ridge that averages approximately 8 feet above sea level. To a depth of 20 feet it is composed of oolitic limestone, which, in turn, is underlain by coral limestone, calcareous sandstone, and sandy limestone of extremely high permeability to a depth of 120 feet. Shelly sandy marl of low permeability occurs from 120 to 160 feet and relatively impermeable clayey silty marl below a depth of 160 feet.

Construction of drainage canals was begun about 1910 and as a result the water table has been lowered several feet. This has allowed salt water to encroach inland 8,000 to 9,000 feet. A balance between fresh and salt water, in accordance with the Ghyben-Herzberg Theory (1:40 ratio) appears to be established for a zone between the shore and 2,500 feet inland. Beyond this zone the actual contact between fresh and salt water is lower than the theoretical contact computed on a 1:40 ratio. It is probable that a balance has not been reached beyond 2,500 feet because of insufficient time since the water table was lowered by drainage, but as time goes on and the salt wedge continues its encroachment, equilibrium will be established farther and farther inland. The salt wedge should finally come to rest where a sufficient weight of fresh water above mean sea level will force the salt water to the bottom of the highly permeable aquifer.

CONTENTS.

INTRODUCTION.

The U. S. Geological Survey, in cooperation with Dade County and the Cities of Miami, Miami Beach, and Coral Gables, began an intensive investigation of the ground water of southeastern Florida in the fall of 1939. This investigation was occasioned by the appearance of salty water in the Miami well field, near the Miami Canal, about 6½ miles inland from Biscayne Bay.

Among the most important problems to be solved during the investigation was that dealing with the source and movement of salt water that had contaminated the well field. Several approaches were made to the problem, by means of which it was determined that the salty water had not come from bodies of connate water, nor directly from the Bay at depth in the aquifer, but had found its ingress up the Miami Canal chiefly during times of low flow in the canal and high tides in the Bay, and had moved laterally from the canal directly into the well field following the gradient of the shallow cone of depression that surrounds the well field.

It is the purpose of this paper to discuss only one of the avenues of approach to the problem—that of the study of salt water encroachment from the Bay at depth in the aquifer.

ACKNOWLEDGMENTS.

The authors are grateful for advice, encouragement, and critical review of this paper by O. E. Meinzer, geologist in charge of the Division of Ground Water of the U. S. Geological Survey, and to V. T. Stringfield, L. K. Wenzel, and S. K. Love, all of that Survey. Recognition is hereby given and appreciation expressed to W. P. Cross, formerly in charge of the Miami office of the U. S. Geological Survey, who originated and directed the methods used in the Silver Bluff studies. Mr. Cross made many of the original computations of the data gathered and wrote a brief memorandum on the subject. To Nevin D. Hoy and John E. Mykytka of the U. S. Geological Survey we are indebted for painstaking assistance in field and laboratory. To the many City and County officials of the Miami area who have actively cooperated with us we are especially grateful. R. H. Brown, who continued the studies after W. P. Cross left for Army duty, wrote a preliminary draft of the subject covered in this paper, but his subsequent departure for Army duty prevented him from taking part in completing the studies, from drawing final conclusions therefrom, and from participating in the final writing for which G. G. Parker is responsible.

HISTORICAL.

Significant studies of coastal ground water were made independently by Badon Ghyben and A. Herzberg shortly before 1900. The results of their investigations are reviewed by John S. Brown, who points out [1] that their theory "appears to apply particularly to small islands and narrow land masses that are made up of freely pervious material, especially sand. It can not be applied to large land bodies or to continents, for it implies that sea water should be found in every locality where the water table is below sea level. There are well known interior land areas which lie many feet below sea level but in which the ground is entirely free from sea water. The application of the theory is also greatly modified by the kind of rocks and their structure.

FIG. 1. Map showing Silver Bluff area, Miami, Florida.

The importance of Herzberg's theory, however, is not to be ignored and has been most convincingly demonstrated by Pennick (Pennick, J. M. K., De "prise d'eau" der Amsterdamsche duin waterleiding: K. Inst. Ing. Tijdschr., 1903–1904, pp. 183–238, The Hague, 1904) on the coast of Holland." Pennick's work clearly demonstrates that salt water underlies the land at a depth of 100 to 200 meters below sea level over a belt several miles wide adjacent to the Holland coast; that the depth to salt water is greatest where the land and the water table are highest; that the zone of diffusion between fresh and

[1] John S. Brown: A study of coastal ground water with special reference to Connecticut. U. S. Geological Survey, Water-Supply Paper 537, pp. 17–19, 1925.

salt water averages about 20 meters in thickness on the North Sea end of the contact; and that the general zone of contact between fresh and salt water is very regular and its center is occupied by the 1000 milligrams per liter isochlor (1000 m.g.l. is approximately equivalent to 1000 p.p.m.). Irregularities in Pennick's isochlor pattern are readily explained by differences in lithology.

The work done by Ghyben and Herzberg developed the following expression for the relation between fresh water and salt water under conditions of equilibrium:

$$h = \frac{t}{g - 1}$$

This may be briefly explained with the aid of the accompanying diagram (Fig. 2) where: t = fresh water head in feet above M.S.L. = kp; h = depth

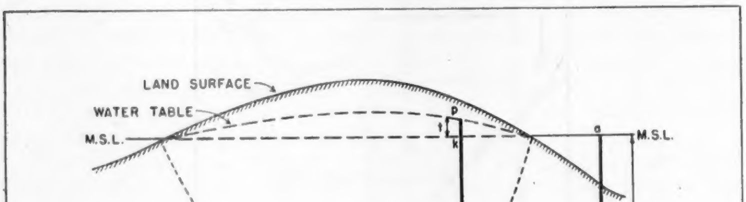


Fig. 2. Diagram showing relation between salt water and fresh water according to the Ghyben-Herzberg Theory.

of fresh water below M.S.L., in feet = ab = ek; g = specific gravity of sea water; $abcdekp$ = outline of a large imaginery "U" tube.

The specific gravity of ground water is assumed to be unity for the development of this relationship. Referring to the "U" tube indicated in the diagram, sea water is considered to fill the part *abcde* and fresh water fills the part *ekp*. Assuming that the fluids in this tube are in static equilibrium it is obvious that pressures at "*e*" and "*b*," points of equal altitude, will be equal. Thus:

Pressure at "*b*" = $(h)\ (g)$
Pressure at "*e*" = $(h + t)\ (1)$

But:

Pressure at "*b*" = Pressure at "*e*"

Hence:

$$h.g = h + t$$

Solving for h gives:

$$h = \frac{t}{g - 1}$$

as shown above. If $g = 1.025$ (a reasonable value for the specific gravity of sea water) then $h = 40t$, or a column of fresh water 41 feet high will exactly counterbalance a column of sea water 40 feet high. Stating it another way, a head of *one* foot of fresh water above M.S.L. indicates a depth of 40 additional feet of fresh water below M.S.L. or a ratio between fresh water head and depth to salt water of 1 to 40. This is the familiar ratio commonly used in predicting the depth at which salt water will be found in a given coastal area. Barksdale[2] has aptly likened the manner in which fresh water, in a narrow coastal or island structure, "floats" on the salt water to the manner in which an ice mass floats on water with most of its volume submerged.

Much of the significant early literature concerning coastal ground water has been ably reviewed in Brown's[3] paper. All of these studies developed relationships and discussed conclusions predicated on the assumption that equilibrium conditions were being considered. Subsequent studies have indicated that in some areas the balance between fresh and salt water is based upon dynamic conditions in which the flow of fresh water adds another factor to the equation. Thus new concepts have been advanced.

In Muskat's[4] treatment of gravity flow systems there appears a discussion of outflow that is pertinent to studies of coastal ground water. It will be remembered that in the Ghyben-Herzberg diagram equilibrium conditions are assumed and the fresh water lens is shown as intersecting the shore line coincident with the mean sea level line. The fact that the upper surface of the lens is actually convex and slopes toward the shore line gives evidence of flow; flow that is balanced by sufficient recharge to maintain an equilibrium between fresh and salt water, obviously based on a long-time hydrologic conditions. On a small island structure, with fresh water in equilibrium with salt water, if the recharge (in this case rainfall) were cut off altogether it is conceivable that the fresh water would ultimately be entirely wasted through persistent outflow near the shore line, around the circumference of the island, and salt water would then be present everywhere at mean sea level. Wentworth[5] points this out in discussing conditions in Honolulu, and Hubbert[6] covers the same material in his paper on ground-water motion. The fact that this complete discharge or loss of fresh water does not occur in many

[2] Barksdale, H. C., Sundstrom, R. W., and Brunstein, M. S.: Supplementary report on the ground water supplies of the Atlantic City region. State of New Jersey, State Water Policy Commission: Special Report 6, p. 25.

[3] Brown, John S.: A study of coastal ground water with special reference to Connecticut. U. S. Geol. Survey Water-Supply Paper 537, 1925.

[4] Muskat, M.: The Flow of Homogeneous Fluids Through Porous Media. McGraw-Hill Book Company, Inc., p. 289, 1937.

[5] Wentworth, C. K.: The specific gravity of sea water and the Ghyben-Hersberg Ratio at Honolulu. University of Hawaii Occasional Paper No. 39, p. 4, 1939.

[6] Hubbert, M. K.: The theory of ground water motion. The Journal of Geology, Nov.–Dec. 1940, Part I, p. 925.

such areas, and the fact that the Ghyben-Herzberg ratio of 1:40 appears to be so nearly realized is in large part due to recharge that occurs over a period of time often enough and in sufficient quantities so that the outflow is balanced and the net or overall effect is the establishment of equilibrium conditions. However, in any study of coastal ground water where outflow is recognized it is desirable to investigate the problem further.

Muskat's observations on outflow at a boundary surface can be compared very closely with outflow along the shore in the Miami area. In the accompanying diagrammatic vertical cross section (Fig. 3), taken normal to

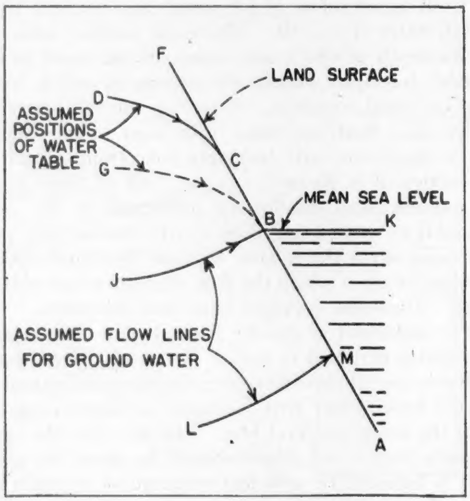


Fig. 3. Diagrammatic vertical cross section showing theoretical flow lines of ground water discharging into the sea.

the short line,[7] line AF represents a sloping shore and mean sea level is indicated by line BK. Line GB represents an assumed position for the curved free surface of the fresh water lens and is drawn sloping downward to meet the shore line at mean sea level in accordance with the Herzberg principle. Since the fresh water surface (GB) is curved some flow is occurring and line GB therefore is also the uppermost or limiting stream line (path traced by a water particle). Line LM represents some stream line below mean sea level where fresh water discharges directly into salt water, and line JB is the particular stream line that intersects the shore line exactly at mean sea level. Hubbert[8] develops mathematical proofs to show that this latter stream line will intersect the sloping shore at an angle of about 90°. It now

[7] Muskat, M.: The Flow of Homogeneous Fluids Through Porous Media. Fig. 89, p. 389, reproduced by permission of McGraw-Hill Book Company, Inc.

[8] Op. cit., pp. 874–884.

becomes apparent, however, that something is wrong with the diagram since the two stream lines GB and JB, plus the many others that could be drawn between them, intersect at point B. This implies that all the flow bounded by these two stream lines can only escape at B or, in other words, that either the flow velocities at B must be infinite to accommodate the discharge, or that water is being lost. It seems reasonable, therefore, to conclude that the assumed position for the fresh water surface, line GB, is in error and that actually it should occupy some such position as that shown by line DC. Fresh water can now be discharged across the boundary BC and the length of this boundary largely will be governed by the amount of water that must be discharged.

The foregoing theoretical observations appear to find confirmation in the Miami area where profiles indicate a water table surface sloping gently downward toward Biscayne Bay. Instead of intersecting the Bay at mean sea level, however, the trend appears to be such that the intersection will occur above mean sea level and in fact even above the high tide level. The profiles further suggest that the vertical length of the boundary or seepage surface is about 0.5 foot.

This might suggest discharge by springs; however, no visible springs now exist along the shore although in the early days before drainage lowered the water table many springs flowed near the base of the limestone cliff along Silver Bluff and elsewhere along the coast.

The wave-cut bench, that forms the land surface between Biscayne Bay and the low sea cliff of Silver Bluff, slopes gently down from 5 feet above mean sea level to the water edge. The water table is never very far below this surface, and the discharge of ground water here through capillary action, evaporation, and transpiration is much in excess of that in areas inland from the cliff. The land surface of the wave-cut bench is always moist, and near the shore is quite damp, indicating continuous ground water discharge.

Wentworth[9] points out that ground water may be discharged without upsetting equilibrium conditions if somewhat isolated leakage channels to the sea exist that do not extend as deep as the line representing U-tube balance. It is entirely conceivable that this does occur in the Miami area, not only leakage along a secondary system of vertical and horizontal solution channels in the limestome, but possibly also through portions of the formation originally more permeable than others.

These two avenues of discharge probably account for the principal discharge of fresh water moving seaward in this area.

Slichter,[10] Hubbert and Muskat have written extensively on the principles governing movement of ground water. Hubbert and Muskat in particular have extended their studies and developed mathematical concepts to explain

[9] Wentworth, C. K.: Storage consequences of the Ghyben-Herzberg Theory. Trans. Am. Geophysical Union, Part II, p. 685, 1942.

[10] Slichter, C. S.: Theoretical investigation of the motion of ground waters. U. S. Geol. Survey, Nineteenth Ann. Rept., pp. 295–384, 1897–98.

Slichter, C. S.: The motions of underground water. U. S. Geol. Survey Water-Supply Paper No. 67, 1902.

Slichter, C. S.: Field measurements of the rate of movement of underground waters. U. S. Geol. Survey Water-Supply Paper No. 140, 1905.

the behavior of fresh ground water discharging into salt water along a coast line. No attempt has been made in this report, however, to develop further these mathematical treatises. Instead, an effort has been made to present in graphical, tabular and descriptive form some of the facts concerning salt water encroachment that have been obtained in this investigation in southeastern Florida.

PHYSICAL FEATURES OF THE MIAMI AREA.

Miami is situated on the Atlantic Coastal Ridge, an irregular, low limestone strip between the lower-lying Everglades to the west and Biscayne Bay to the east. Biscayne Bay itself is a very shallow body of water separating the ridge from Miami Beach and the Atlantic Ocean. The ridge is scarcely noticeable as such. It rises almost imperceptibly from the Everglades and falls almost as imperceptibly to the Bay. Its altitude averages, perhaps about 8 feet above mean sea level. Along one short stretch of shore, Silver Bluff in the Coconut Grove section of Miami, a low Pleistocene sea cliff (Fig. 5) is cut in the oolite that composes the ridge. The foot of the cliff is a wave-cut notch that stands 5 feet above mean sea level, and marks the head of a gently sloping wave-cut bench. At 8 feet above mean sea level is another wave-cut notch probably produced at the same time that the 5-foot notch was being cut, but by action of storm waves, or it may have been produced by a separate halting stand of the receding late Pleistocene (Pamlico) sea at that height. These wave-eroded features may be traced elsewhere in the Miami area along the coast line but nowhere else are they so plainly exhibited as at Silver Bluff. These, and many other features of south Florida, have already been described by Parker and Cooke.[11]

Miami has a semi-tropical climate with an average rainfall of about 59 inches per year. There are usually distinct wet and dry seasons each year that last, respectively, from June through October and from November through May. The prevailing winds are from the southeast; and transpiration and evaporation are very high the year around.

The geological factors bearing on the problem are fairly simple and are illustrated in Figs. 4, 6, and 8. Fig. 4 is a block diagram of the Greater Miami Area graphically showing the structure and physical features of the coastal area. Silver Bluff is depicted at the extreme left on the western shore of Biscayne Bay. The principal drainage canals are shown cutting through the Atlantic Coastal Ridge excepting only the Coral Gables Canal, which empties into Biscayne Bay south of the boundary of the diagram.

Fig. 6 is a generalized geologic cross section generally typical of conditions in the Miami area, taken in a direction approximately normal to the western shore of Biscayne Bay and extending about 29 miles inland along the Tamiami Trail (U. S. Highway 94).

The section indicates the presence of a long wedge-shaped structure divided into three rock formations: the Miami oolite (Pleistocene), the Key Largo limestone (Pleistocene), and the Tamiami formation (Pliocene).

[11] Parker, Garald G., and Cooke, C. Wythe: Late Cenozoic geology of southern Florida. Fla. Geol. Survey Bull. 27, 119 p., 26 pl., 4 figs., 1944.

These highly permeable formations transmit oceanward large quantities of fresh ground water. Although some ground water probably moves through the sandy, silty and shelly upper portion of the Hawthorn formation (Miocene) it is very slight in comparison to the movement through the overlying materials, and no appreciable movement occurs through the underlying clayey portions of the Hawthorn.

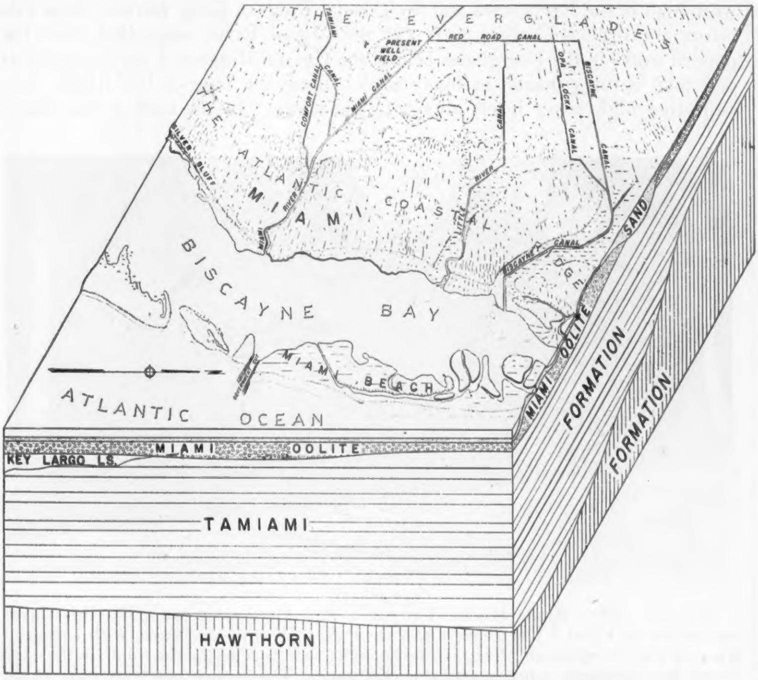


FIG. 4. Block diagram of Miami area.

The length of the wedge of permeable rocks shown in the diagram is about 29 miles. Its thickness ranges from about 25 feet in the west to 125 feet in the east. Computations indicate that over 15 million gallons of ground water may be stored in each foot of width of this wedge, assuming an average specific yield of 18 per cent. The specific yield is defined as the ratio of volume of water released by gravity, to volume of the water-bearing material unwatered.[12]

This large volume of water is supplied principally by direct downward percolation of rains that fall on the land surface over the wedge. Some of

[12] Meinzer, O. E.: The occurrence of ground water in the United States. U. S. Geol. Survey Water-Supply Paper 489, p. 51, 1923.

the water, however, is supplied by canal flow from runoff in adjacent areas and some is supplied by rainfall and canal flow in the outcrop area of the Tamiami formation west of the western limit of the cross section.

GENERAL GROUND WATER CONDITIONS IN THE MIAMI AREA.

Rainfall has always been sufficient so that in the past ground water levels were high in the Everglades and the Coastal Ridge. Early records show that before the drainage canals were cut the Miami River descended from the ponded water in the Everglades behind the Coastal Ridge in a rapids, and that perennial springs flowed in many places along the base of the Ridge, thus indicating high water levels almost to the shore. In the face of this heavy

FIG. 5. Silver Bluff, Miami, Florida, a late Pleistocene sea cliff with wave-cut notches at 8 and 5 feet above mean sea level and wave-cut bench, with road and lawn, in the foreground. The 5-foot notch is that formed at the foot of the cliff where the wave-cut bench meets the cliff face. The 8-foot notch is seen as an undercut area in the cliff face on an old headland at a point where the cliff makes a right-angled bend inland. Photo by Garald G. Parker, U.S.G.S.

discharge of fresh water, salt water could not have been encroaching in the highly permeable aquifer of the Miami area prior to the construction of the drainage canals.

Exploration by means of test wells indicates that along the Coastal Ridge and back into the lower Everglades [13] the formations from Pleistocene downward through upper Miocene had been flushed of their highly saline waters,

[13] Parker, Garald G.: Notes on the geology and ground water of the Everglades in southern Florida. Proc. Soil Science Society of Florida, vol. IV-A, p. 47–76, 1942.

Parker, Garald G., and Hoy, Nevin D.: Additional notes on the geology and ground water of the Everglades in southern Florida. Proc. Soil Science Society of Florida, vol. V, p. 33–55, 77–94, 1943.

and that farther inland, especially near Lake Okeechobee, there are still large areas containing modified connate water and/or bodies of mineralized water residual since the high-sea levels of the interglacial ages of the Pleistocene.

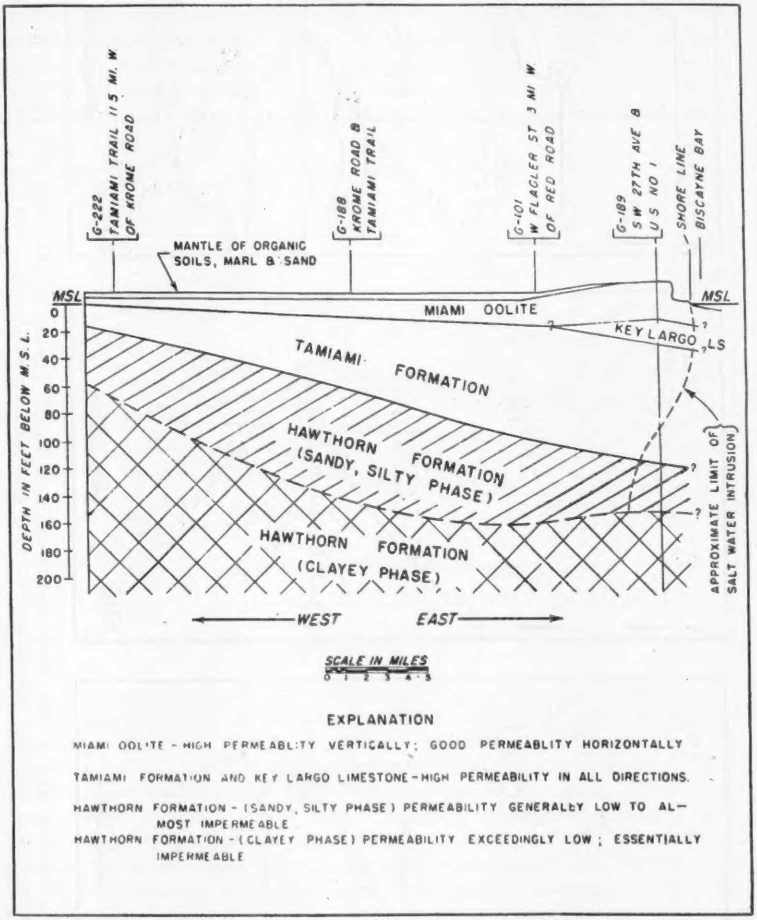


FIG. 6. Generalized east-west cross section along Tamiami Trail, Dade County, Florida.

On the mainland, in the Miami area, these formations (including the Miami oolite, Key Largo limestone, Tamiami formation and at least the upper part of the Hawthorn formation) were flushed of their salty waters and filled

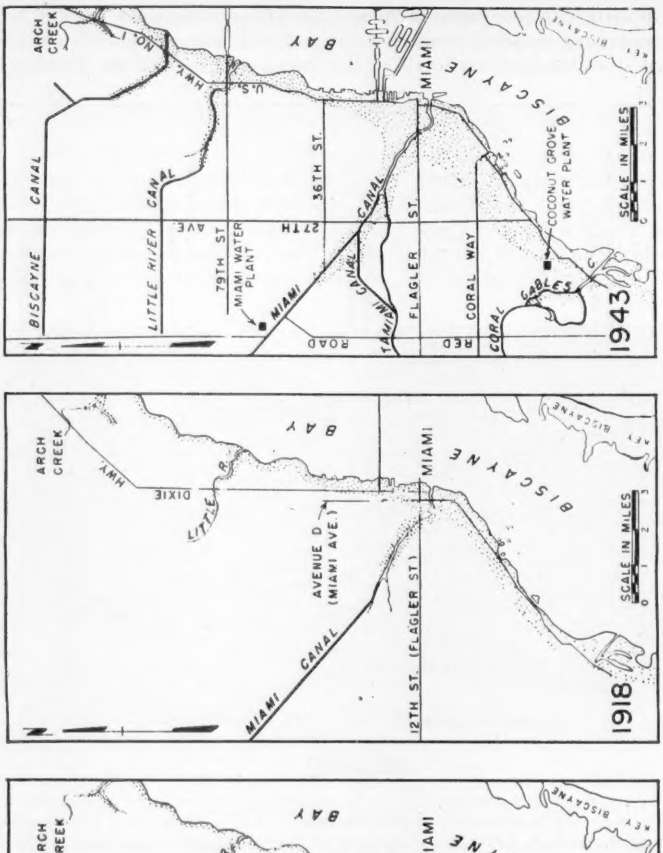


FIG. 7. Maps showing areas of salt water contamination at Miami, Florida, in 1904, 1918, and 1943. (Note: Stippling shows extent of areas that have chloride concentration approximating 1000 p.p.m. or more, at a depth of about 80 feet.)

with potable ground water. The flushing action probably took place during the low-level stands of the sea during the several Pleistocene glacial ages. With the rise in sea level during Recent time a concomitant rise in ground water prevented an encroachment of sea water into the aquifer above the relatively impermeable part of the Hawthorn formation. Thus, before man began modifying natural conditions, the formations along the coast in southern Florida were filled with fresh, potable ground water, and it is only since his drainage operations began that the balance between salt and fresh water was upset, and salt water began migrating inland at the expense of fresh water.

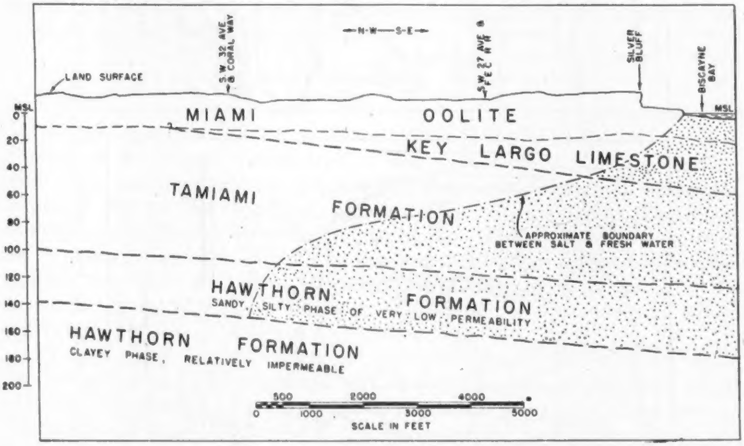


FIG. 8. Cross section showing approximate extent of salt water encroachment in the Silver Bluff area.

Fig. 7 shows maps of the Miami area indicating conditions of salt and fresh water in 1904, 1918, and 1943. The maps for 1904 and 1918 are largely based on estimated and known conditions, but the map for 1943 is based on samples from wells generally more than 80 feet deep. These maps clearly show the trend of salt water advancing inland and displacing fresh water. They show that salt water has not yet reached the Miami well field by direct infiltration from the Bay at depth in the aquifer, and likewise show why it was necessary in 1941 to abandon the ground water supply from the Coconut Grove water plant.

The approximate limit of salt-water encroachment in the Silver Bluff area is shown in Fig. 8. On the landward side of the broken line drawn through the diffusion zone between fresh water and salt water, annual precipitation averaging around 59 inches serves to recharge the highly permeable formations and to maintain sufficient overall head that will prevent the movement of encroaching salt water beyond a certain zone.

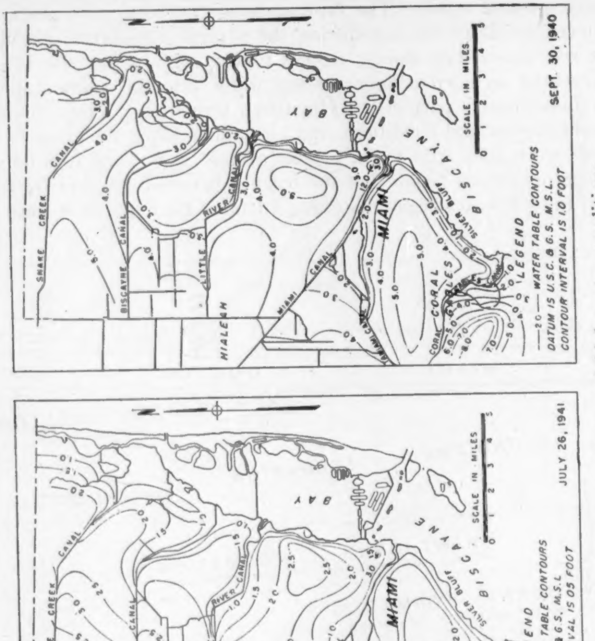


FIG. 9. Water table maps, Miami, Florida, for low, medium, and high water conditions.

On the seaward side of the boundary line daily tidal cycles and seasonal and long time trends operate to advance salt water encroachment. Daily tidal cycles in Biscayne Bay average around 2 feet in height, and seasonal trends in tidal stages range about a foot. Under the maximum combination of these fluctuations, however, the greatest tidal stage seldom exceeds 2 feet for a period longer than a week.

The maps, Fig. 9, are of the Miami area and show ground water contours during periods of extremely high, fairly low, and just above average stages of the water table. They indicate the normal ranges of fluctuation of the water table and the directions of flow of the ground water during the period of observation (ground water flow is always at right angles to the contours on the water table).

STUDIES IN THE SILVER BLUFF AREA OF MIAMI.

Selection of the site for study. Inasmuch as field investigations indicated that the geologic cross section as shown in Fig. 8 would be generally typical throughout the Miami coastal area, it was possible to confine the detailed parts of the salt water encroachment studies to one small area with reasonable assurance that the observed conditions would likewise be typical. The Silver Bluff area was selected for intensive investigation because it appeared to offer the largest number of wells ready to use, and because the depths of the wells ranged from about 45 feet to 100 feet, thus giving a good sampling of the permeable rocks. Fig. 1 shows the general location of the study area within the metropolitan limits of Miami.

Preliminary work. Considerable preliminary work was required before the first study could be attempted. A thorough inventory was made of all available fire wells and drainage wells to determine the areal and the vertical distribution of points of access to the ground water body. Results of this inventory indicated that the coverage would be satisfactory at least until the true nature of the problem could be better defined. For purposes of determining the altitude of the water table fourteen observation wells, 2 inches in diameter, were driven so that they would scarcely do more than pierce the water table and yet be deep enough so that they would not go dry during drought periods. Wherever possible or convenient the wells were installed adjacent to existing fire wells to permit a direct comparison between the true water table, as found in the shallow observation wells, and the apparent water table, as found in the deeper fire wells. Where both wells of any pair ended in ground water of normal chloride concentration (about 16 p.p.m.) or, more properly, where the specific gravity of the ground water in each well was the same, it was expected that the water levels in the two wells would be nearly identical. Close to the Bay, however, where fire wells tapped ground water of high chloride concentration and where the specific gravity of the water in the well casings was therefore appreciably greater than the specific gravity of water in the shallow observation wells, it was expected that the apparent water table would be appreciably lower than the true water table. Subsequent studies proved this to be true, and results of these studies will be published later. Fig. 10 shows the locations of wells used in the Silver Bluff studies.

In order that full data might be obtainable on the tides and sea level in Biscayne Bay and their effect on the water table be studied, a continuous water stage recorder was installed in the Bay at the foot of Aviation Avenue in November, 1940, and records have been obtained since November 8 of that year. The record shows, among other things, that the average sea level during the course of this investigation has been higher than established U. S. Coast & Geodetic Survey mean sea level, and that there is a tendency for the mean tide stage to increase.

A summary of the record for the period preceding the studies herein reported follows:

Nov. 8, 1940 to July 26, 1941		
229 maximum stages, average	+1.44′	U.S.C. & G.S. msl.
229 minimum stages, average	−0.66′	"
	2 | +0.78′	"
Average mean sea level	+0.39′	"
July 26, 1941 to February 4, 1942		
207 maximum stages, average	+1.52′	U.S.C. & G.S. msl.
207 minimum stages, average	−0.52′	"
	2 | +1.00′	"
Average mean sea level	+0.50′	"
November 8, 1940 to February 4, 1942		
436 maximum stages, average	+1.48′	U.S.C. & G.S. msl.
436 minimum stages, average	−0.59′	"
	2 | +0.89′	"
Average mean sea level	+0.45′	"

Objectives. Three important objectives had to be reached through these studies. It was necessary first to obtain a clear definition of the horizontal and vertical distribution and extent of the salty ground water; second, to determine the magnitude of seasonal shifts or changes in the encroaching salt water wedge; and third, to discover whether or not the salt water wedge is gradually moving inland and contaminating parts of the aquifer formerly containing only fresh ground water. The first objective could have been reached through a single study; the second and third objectives, however, necessitate repeated studies over a variety of seasonal conditions, and actually need to be continued over a much longer period of observation than the writers have been able to use.

Procedures. The first intensive study in Silver Bluff was made on June 26, 1941. Results of this study were valuable primarily in devising efficient and thorough methods for conducting later studies. The field procedures that were adopted were as follows:

1. Selection of a date for conducting a study was based on a review of rainfall records for the preceding several days. Since it was known that about 17 drainage wells scattered throughout the area, and numerous others in the adjoining area, received the discharge from storm sewers and catch basins, it appeared that for several days following heavy rains the water table

around these wells was distorted. In effect the drainage wells acted as local recharge points for the water body and no study was attempted, therefore, unless 3 or 4 days had elapsed since the last heavy rains.

2. All fire wells selected for observation in the area were pumped with a portable pump powered by a gasoline engine. The pumping was done on the day preceding the date chosen for a particular study. In general, the fire wells were pumped in the approximate order of their estimated chloride concentrations with those wells in which concentrations were highest being pumped first. This made it certain that if for any reason all the fire wells could not be pumped on the day preceding the study those remaining to be pumped would be low in chloride content. Thus there would be no appreciable change, due to pumping, in the water level within these wells on the day of the study. Each well was pumped long enough so that the casing would be entirely emptied of water standing in the well and would be refilled with water drawn from the aquifer at the known depth of the well. A water sample was collected as soon as the pump had removed the stale water which stood in the well.

3. On the date selected for a study, water levels in all fire wells and observation wells were measured at hourly intervals over a thirteen-hour period so that for any wells responsive to tidal variations one complete tide cycle would be obtained. Drainage wells were not used either for sampling or for observation purposes since they contained large amounts of sludge and debris that affected both the quality of the water and the altitude of the water level in the well.

The field work just outlined was directed toward the objective of preparing in the office a composite cross section taken in a direction normal to the general trend of the shoreline, showing the profile of the water table and the ischlors. The profile of the water table was based entirely on observations in the shallow wells and the isochlors were based on chloride determinations of samples collected from fire wells.

In compiling results of the first study the shortest distance from each well to the shore was determined, taking advantage of the many irregularities in the shoreline. The water table profile resulting from the use of these distances, however, appeared excessively uneven, so a smooth curve was drawn to represent an approximate average shoreline (see Fig. 10). The shortest distance from a well to the shore then became the length of the normal, erected to the average shoreline, passing through the well. Using these distances the water table profile was readily plotted as a fairly smooth curve.

Description of studies. Four complete salt water encroachment studies were made in the Silver Bluff area following the study of June 26, 1941. These studies, made on July 26, 1941, August 28, 1941, October 25, 1941, and February 4, 1942, covered water table levels ranging from a stage slightly above medium to a fairly low stage. Of the four studies the one on July 26 covered the highest water table levels and the one on February 4 the lowest. Data for these two studies are presented in this report so that the maximum observed seasonal changes in the salt water encroachment pattern may be noted.

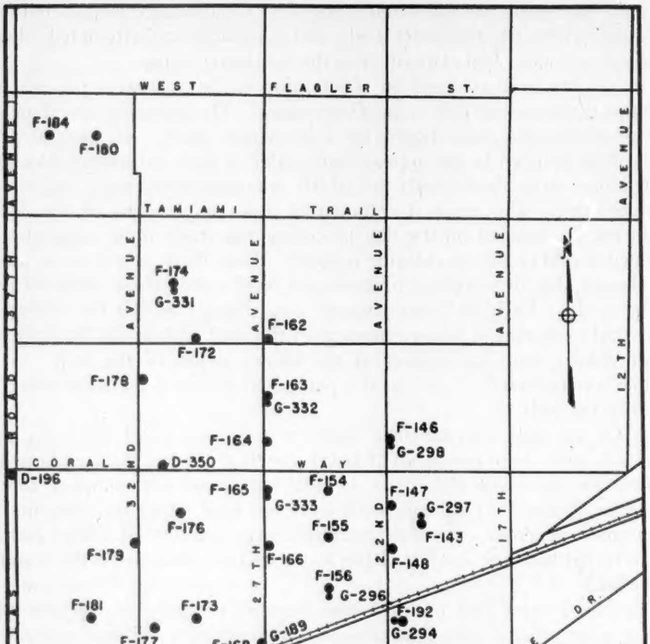


FIG. 10. Map of the Silver Bluff area, Miami, Florida, showing the location of wells used in the studies of salt-water encroachment.

TABLE I.

SALT WATER ENCROACHMENT STUDIES—SILVER BLUFF AREA, MIAMI, FLORIDA.
SUMMARY OF DATA COLLECTED ON JULY 26, 1941 AND FEB. 4, 1942.

Well No.	Distance from Shoreline (in feet)[a]	Land Surface Altitude	Altitude of M.P.	Depth of Well Below M.P.	Depth of Well Below M.S.L.	Mean Water Level Altitude 7-26-41	Chloride in p.p.m. 7-25-41	Specific Gravity 7-25-41	Mean Water Level Altitude 2-4-42	Chloride in p.p.m. 2-3-42	Specific Gravity 2-3-42
F184	14,840	14.7	16.31	88.2	71.9	0.99	20[b]	1.0000	0.40	20[c]	1.0000
F180	14,240	13.5	15.28	63.6	48.3	1.45	17[b]	1.0000	0.83	16[c]	1.0000
F174	10,820	12.7	14.67	69.0	54.3	2.24	24[b]	1.0000	1.18	25[c]	1.0000
G331	10,820		12.95	14.1	1.1				1.22		
F172	9,380	12.2	14.18	89.5	75.3	2.19	49[b]	1.0000	1.17	46[c]	1.0000
F178	9,500	10.7	12.64	68.2	55.6	2.22	26[b]	1.0000	1.20	25[c]	1.0000
F162	8,680	10.7	12.29	75.2	62.9	2.21	555[b]	1.0007	1.18	620[c]	1.0008
F163	7,760	13.1	14.81	63.4	48.6	2.23	40[b]	1.0000	1.23	41[c]	1.0000
G332	7,760		13.50	14.2	0.7	2.24			1.21		
F146	5,680	7.7	9.73	110.5	100.8	0.29	16,600[b]	1.0222	−0.58	16,700[c]	1.0223
G298	5,680		8.48	10.5	2.0	2.18			1.31		
F164	6,800	12.9	14.70	80.1	65.4	2.16	143[b]	1.0002	1.21	203[c]	1.0002
F165	6,020	7.7	9.70	63.3	53.6	2.14	113	1.0001	1.22	163[c]	1.0002
G333	6,020		8.11	9.0	0.9	2.19			1.23		
F154	5,340	12.2	14.23	83.8	69.6	2.11	730	1.0009	1.22	780[c]	1.0010
F147	4,420	10.3	11.80	67.6	55.8	2.10	215	1.0003	1.32	248[c]	1.0003
F143	3,640	10.5	12.09	100.8	88.7	0.51	15,440	1.0206	−0.14	16,800[c]	1.0224
G297	3,640		11.09	12.0	0.9	1.98			1.40		
F166	5,060	9.9	11.78	62.7	50.9	2.10	86	1.0001	1.24	102	1.0001
F155	4,380	7.0	8.48	62.0	53.5	2.07	157	1.0002	1.26	136	1.0002
F148	3,620	11.1	13.11	70.5	57.4	2.03	135	1.0002	1.34	245	1.0003
F156	3,580	12.4	13.75	91.9	78.1	1.43	6,120	1.0081	0.22	13,100	1.0175
G296	3,580		13.18	14.0	0.8	2.03			1.30		

TABLE I.—*Continued.*

Well No.	Distance from Shoreline (in feet) [a]	Land Surface Altitude	Altitude of M.P.	Depth of Well Below M.P.	Depth of Well Below M.S.L.	Mean Water Level Altitude 7-26-41	Chloride in p.p.m. 7-25-41	Specific Gravity 7-25-41	Mean Water Level Altitude 2-4-42	Chloride in p.p.m. 2-3-42	Specific Gravity 2-3-42
[F192	2,080	10.7	12.56	78.3	65.7	0.98	11,670	1.0155	0.33	13,900	1.0185
G294]	2,080		10.99	12.0	1.0	1.73			1.28		
[F149	1,480	10.8	12.64	86.1	73.5	0.30	17,940	1.0240	−0.04	17,800	1.0238
G295]	1,480		11.73	14.3	2.6	1.64			1.22		
G48	2,300	10.0	10.28	13.0	2.7	1.75			1.23		
[F158	2,560	12.1	13.72	85.0	71.3	0.53	15,970	1.0213	0.04	16,100	1.0215
G158A]	2,560		12.32	16.4	4.1	1.71			1.20		
[F198	1,960	11.8	13.79	69.2	55.4	1.48	6,120	1.0080	0.86	8,240	1.0109
G293]	1,960	10.4	11.58	14.2	2.6	1.68			1.20		
F199	2,020	17.6	18.87	89.9	71.0	0.45	16,600	1.0222	0.09	16,700	1.0223
F213	1,320	16.4	18.38	71.1	52.7	1.30	4,990	1.0065	0.70	9,220	1.0122
F176	6,540	10.0	12.29	88.4	76.1	2.04	508	1.0006	1.26	545	1.0007
F179	6,680	8.8	11.17	79.5	68.3	2.03	246	1.0003	1.15	315	1.0004
F181	6,180	5.5	7.15	54.1	46.9	1.93	299	1.0004	1.21	310	1.0004
F173	4,680	9.0	11.45	62.6	51.2	1.97	458	1.0006	1.16	522	1.0006
F177	5,120	5.8	7.85	57.5	49.7	1.87	246	1.0003	1.15	272	1.0003
F168	3,440	11.6	13.57	108.6	95.0	0.45	15,640	1.0209	−0.25	17,100	1.0229
F191	3,940	14.0	16.33	68.6	52.3	1.77	183	1.0002	1.17	206	1.0002
F188	2,400	17.1	18.50	116.7	98.2	0.28	17,750	1.0237	−0.13	18,000	1.0241
F202	1,860	15.5	17.89	64.4	46.5	1.53	450	1.0006	1.12	680	1.0008
G43	1,800	5.0	6.00	11.8	5.8	1.50			1.10		
F159	1,900	16.1	17.40	86.8	69.4	0.43	16,790	1.0224	0.03	17,100	1.0229
[F160	840	14.5	16.19	65.6	49.4	1.33	2,225	1.0028	0.72	8,000	1.0106
G292]	840		14.94	16.8	1.9	1.45			1.11		
G334	180	4.3	4.89	7.0	2.1	1.34			1.06		

[a] Measured normal to an arbitrary curve drawn to represent an average shore line.
[b] Sample collected on July 26, 1941.
[c] Sample collected on February 4, 1942.

All altitudes are given in feet referred to UCS & GS M.S.L.
Brackets indicate pairs of wells at the same locations.

Table 1 summarizes the data collected in these two studies and Figs. 11 and 12 give the resulting composite profiles indicating isochlors and water tables. On each of these profiles there has also been drawn a line representing the theoretical position of the boundary between fresh water and salt water, assuming perfect application of the Ghyben-Herzberg theory. The position of this line was determined by using an average specific gravity for sea water (referred to normal ground water as unity) of 1.025 and thereby developing a ratio of 1 : 40 for the relation between fresh water head above mean sea level and depth to which fresh water extends below mean sea level. Using this ratio computations were then made for enough selected points

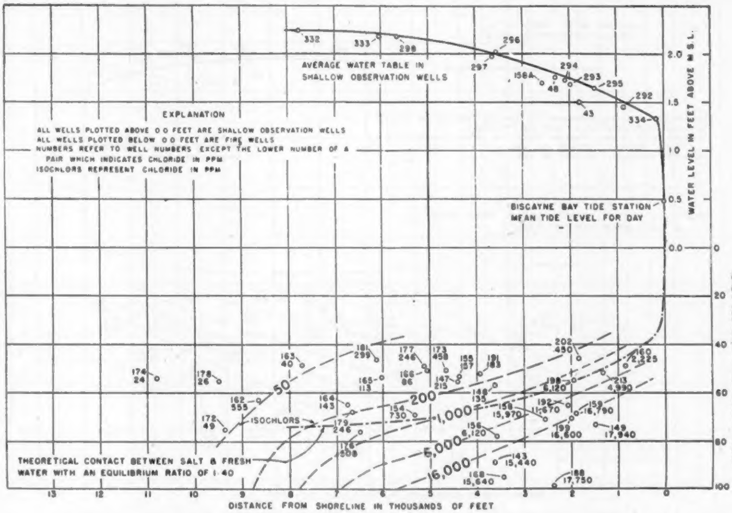


FIG. 11. Composite profile for salt-water encroachment study of July 26, 1941, Silver Bluff area, Miami, Florida.

along the water table curve so that the Ghyben-Herzberg equilibrium line would be well defined.

In selecting the 1:40 ratio the writers took into account the ranges in specific gravity observed in the nearby ocean water, in the water of Biscayne Bay, and in the salty ground water of Silver Bluff itself. On the basis of the specific gravity of sea water the ratio would have been 1 to 37.8, but values ranging up to 1 : 42 were noted for the Bay and in the encroaching salty water wedge of Silver Bluff. From these facts it was decided that use of an average figure, 1 : 40, would be most desirable.

The mean gage heights of sea level in Biscayne Bay for the days of study in each case were above U.S.C. & G. S. mean sea level. On July 26, 1941 the gage height was 0.47 foot, and on February 4, 1942 was 0.49 foot above mean sea level. However, the mean gage height for any given day is not the logical measurement to use as a datum in correcting for salt water-fresh water balance as of that day; rather, the average sea level for a considerable period if time preceding the study should be used. Thus, for the July 26 study an average sea level of + 0.39′ was used and for the February 4 study + 0.45′ was used (see p. 250).

Since the ratio of scales used in plotting the water table and the isochlors was 1 : 40 the Ghyben-Herzberg equilibrium curve is very nearly an exact inversion of the water table curve. It is significant to note that on the profile for July 26 the Ghyben-Herzberg equilibrium line parallels the entire isochlor

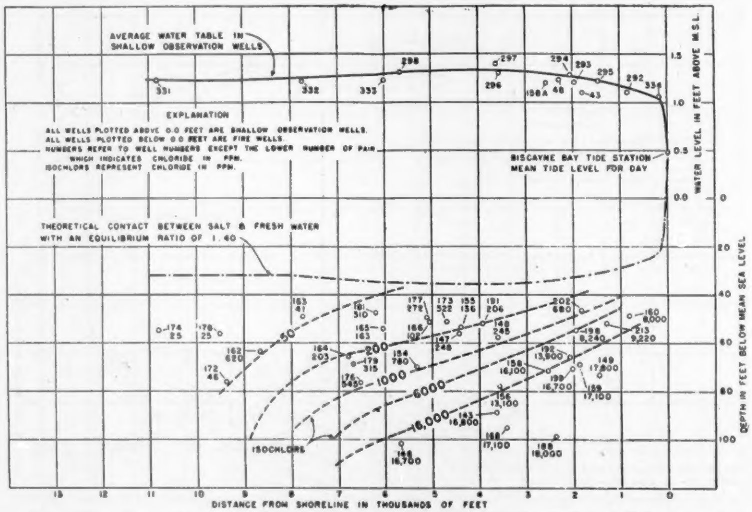


FIG. 12. Composite profile for salt-water encroachment study of February 4, 1942, Silver Bluff area, Miami, Florida.

pattern inland to about 2,500 feet, and lies below the 1,000 p.p.m. isochlor inland to about 4,800 feet; whereas on the profile for February 4 it lies above the entire plotted isochlor pattern. In spite of this great difference there is no proportionate shift in the isochlor pattern. This is a graphical illustration of the fact that a change in the water table altitude does not immediately provoke a change 40 times as great in the altitude of the isochlor pattern. Superimposing the 2 composite profiles (Fig. 13) shows that the altitude of the water table on February 4 ranges from 0.3 to 1.0 foot lower than on July 26. The altitude of the isochlor pattern for February 4, however, averages only about 4 feet higher than on July 26. This slight change was anticipated since Wentworth[14] had previously shown that an adjustment of the equi-

[14] Wentworth, C. K.: The specific gravity of sea water and the Ghyben-Herzberg ratio at Honolulu. Univ. of Hawaii Bull., vol. 18, no. 8, June 1939.

librium between salt and fresh water to change in water table altitude lags far behind the time of water level change because it involves actual changes in "bottom storage" that cannot be made quickly.

In Fig. 13 the chloride data are given for 3 wells drilled within the limits of the Silver Bluff study area at different times prior to July 26. Water samples were collected by the U. S. Geological Survey as the wells were being drilled, therefore, reliance can be put in the chloride figures for given depths. The data for the two drainage wells, D196 and D350, indicate sharp downward trends of the isochlors in the area that lies from 6,000 to 8,000 feet back from the shore line. It may be stated, therefore, that in general the inland

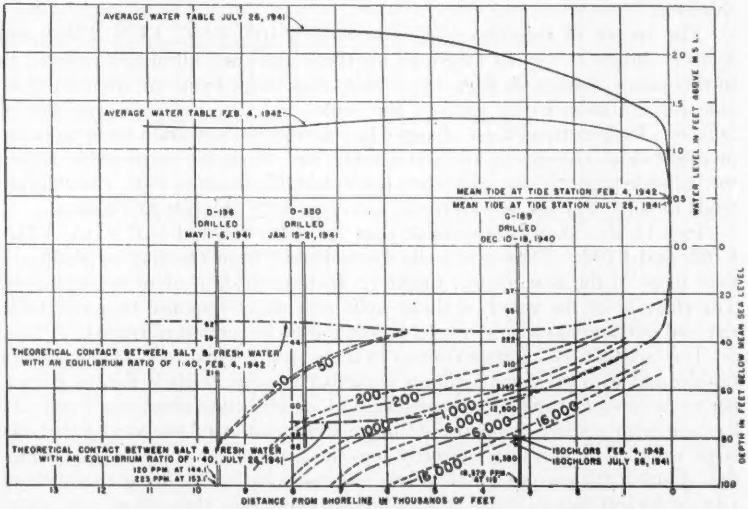


FIG. 13. Composite profiles for salt-water encroachment studies of July 26, 1941 and February 4, 1942, Silver Bluff area, Miami, Florida.

extent of salt water encroachment in the Silver Bluff area at depths below 80 feet is about 8,000 feet. The actual inland penetration of chloride in a concentration comparable to that of sea water is not known, but based on the data obtained from the drilling of well D196 it is evident that it is less than 9,600 feet, and samples pumped from well F146 indicate it is more than 5,600 feet. Somewhere between these boundaries, therefore, is the maximum inland penetration of high chloride concentration.

The chloride data for test well G189 fit in satisfactorily with the isochlors as drawn for July 26. Although inspection of these data suggest that these isochlors have been drawn at too low an altitude it should be noted that the test well was drilled in December 1940 at a time when the water table was lower than on July 26, 1941. Thus the chloride pattern as indicated by the well samples would be expected to appear at an altitude slightly higher than shown by the isochlors.

Although only four comprehensive encroachment studies were undertaken in the Silver Bluff area, considerable supplemental data are available through periodic water level observations and chloride analyses of well water. In Fig. 14 chloride results are given for water samples collected from wells in the Silver Bluff area plotted against time. Also shown on the graph, for comparison, is a hydrograph of F179, a well on which a continuous water stage recorder is maintained. F179 is 6,680 feet inland from the Bay. This is the greatest distance that recognizable tidal effect has been noted in wells. The water level of F179 may be taken as representative of the other wells in this area.

The record of chloride changes in wells F160, F156, F198, F192, and F146 is shown in Fig. 14 (the data for these wells and all others referred to in this paper appears on page 44). Note that, in general, the trend in chloride concentration in all wells is the same, and that they rise and fall in unison. Furthermore, these changes in chloride concentration seem to occur in response to changes in the water table, *i.e.*, when the water table is low the chloride tends to rise, and when the watertable becomes high, the chloride tends to fall. The net overall trend, however, is for chloride to increase.

Fig. 14 also shows comparable data for wells F174, F163, F165, F147, F162, and F202. These are wells more distant from the Bay or shallower than those of the first group; therefore, their chloride content is much less. The chloride in the water of these wells also show response to water table rise and fall, and likewise show net increase over the period of record.

The fact that the chloride content in the water of some wells changes more rapidly and with greater magnitude than that in other wells is due to a number of factors; (1) distance from Bay, (2) depth below mean sea level, (3) location with respect to nearby drainage wells that may introduce relatively large volumes of rain water directly into the body of the salt water at depth, thus diluting the ground water locally and temporarily upsetting equilibrium, (4) geological factors such as solution channels that may allow salt water easy access to the area or, conversely, may allow fresh water to discharge freely to the sea.

RESULTS OF SILVER BLUFF STUDIES.

Effects of rains on the ground water. As indicated previously, selection of optimum times for conducting salt water encroachment studies in the Silver Bluff area was not always easy. Heavy rains occurring just before or during a study would cause local distortions in the water table and isochlor pattern sufficient to upset the most carefully collected data. Nevertheless it was important to obtain information for high water table conditions; accordingly the study of July 26, 1941 was conducted just after the rainy season peaks that occurred around July 13 (Fig. 14, hydrograph of F179). Close inspection of the composite profile given in Fig. 11 indicates that at many points the isochlor pattern does not entirely satisfy the chloride concentrations shown for the various wells. Apparently, therefore, even though the study was made

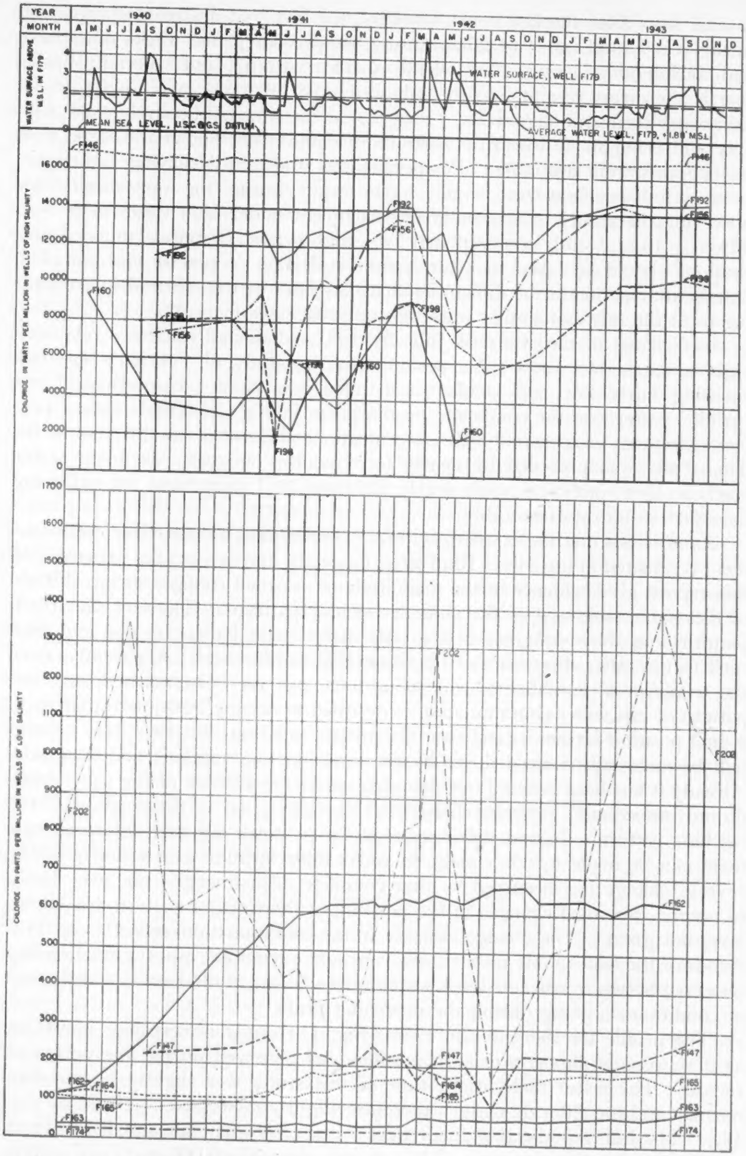


FIG. 14. Graph showing fluctuations of the water level in well F179, and chloride content of water in eleven wells in the Silver Bluff area, Miami, Florida, April 1940 to December 1943.

several days after the last heavy showers, the fact that a sizeable proportion of the year's total rain had fallen during the preceding few weeks must have had considerable lasting effect on the isochlor pattern; and especially upsetting is the direct receipt into the salt wedge of relatively large quantities of rain water from drainage wells. Progress at the time of the study was probably still being made toward conditions of equilibrium but at the same time water levels were declining. Postponing the study until varying factors became stabilized, however, would have meant losing the opportunity for observing the nature of salt water encroachment under high water table conditions. In any study contemplated for a high period, therefore, unusual precautions should be taken to insure ample collection of precise and complete data in anticipation of the difficulties that may later be experienced in attempting to fit the results together into one comprehensive picture.

In contrast to the study of July 26, 1941, conducted during a relatively high and unstable water table period, was the study of February 4, 1942, covering fairly low and stable water table conditions. Inspection of the isochlor pattern on the composite profile given in Fig. 12 reveals almost perfect agreement with the chloride concentrations shown for the different wells. This study was preceded by nearly four months of steady declining water levels so that conditions were nearly stabilized and were ideal for gathering data that would plot smoothly.

Equilibrium and the isochlor pattern. The studies of salt-water enchoachment conducted in the Silver Bluff area, especially the two studies presented in this report, give evidence of the magnitude of seasonal changes in the altitude of the water table and of the shift of isochlor patterns. The fact that these patterns can show progress first in one direction and then reverse and proceed in the other direction is of considerable significance. Apparently, over the whole area, equilibrium conditions have not yet been reached, and the pattern of salt water contamination is destined to occupy, at some future date, a final position farther inland from its present position; however, this process will be materially slowed down by the seasonal interruptions and reversals. Already it has been pointed out that changes in the altitude of the water table do not immediately provoke changes 40 times as great in the position of the isochlor pattern. Indeed there seems to be so much lag that before adjustment can be made to one change in water-table altitude a new and possibly reverse change has occurred so that complete adjustment is not ever likely to occur. Seasonal changes in the position of the isochlor pattern are, therefore, not great. The changes in salt water contamination reflect long term trends of the water table rather than overnight variations, and the relationship observed between salt and fresh water in the Silver Bluff area is a reflection of conditions existing during the preceding years.

The profile for the July 26, 1941 (Fig. 11) study is revealing inasmuch as it represents almost normal conditions—as observed during the period of record. The water table at the time of this study was slightly higher than normal, and the chloride pattern therefore slightly depressed. (See also Fig. 14.) The line representing theoretical contact between salt and fresh water parallels the isochlor pattern and lies slightly above the 6,000 parts per million isochlor inland for about 2,500 feet. This indicates that equilibrium, based on average yearly values, is probably established over that distance. Beyond 2,500 feet the theoretical line gradually flattens out and at about 4,800 feet crosses the 1,000 parts per million isochlor. Thus equilibrium is not far from being realized almost 4,800 feet inland. Beyond this point, however, the divergence between the theoretical line and the isochlors is great.

Fig. 13 shows the relatively small amount of actual shift involved in the isochlor pattern between very low and slightly above medium water table stages and supports the conclusion that equilibrium, based on average yearly water table altitudes, has been reached at least 2,500 feet inland, and that such low-water stands as that of February 4, 1942, are only related to the salt-water encroachment pattern insofar as they enhance movement of salt water inland. Certainly the isochlor pattern and the theoretical balance line as of February 4, 1942 show no direct correlation, whereas there is good correlation as of July 26, 1941. The isochlor pattern is a result of average conditions prevailing over a long period of time, and is very slowly progressing inland, but is constantly subject to slight advances and retreats. It probably can never advance farther inland than the average yearly position of the two and one-half foot contour on the water table, because with that much height of fresh water above mean sea level the salt wedge would be completely depressed to the relatively impermeable clayey marls of the Hawthorn formation that underlie the highly permeable aquifer, and the salt-water advance would halt there.

The writers believe that the seaward flow of fresh water over the wedge of salty water may possibly have some depressive effect on the wedge, but if so it probably is of only a minor magnitude and cannot account for the rapid vertical descent of the isochlors beyond 7,000 feet from the shore. Rather, the cause is to be looked for in a residual lag from conditions prevalent in the past—there has been a relatively short period of time for the salt wedge to advance since the cutting of drainage canals through the Coastal Ridge. These steeply dipping isochlors merely mark the inland margin of the encroaching salt wedge. They will likely retain their general pattern as the wedge continues to encroach, but as time goes on they will advance farther inland until, as noted above, the movement will be stopped at the location of the average annual two and one-half foot contour on the water table.

SUMMARY AND CONCLUSIONS.

From all these considerations the writers conclude that: (1) Before drainage operations were begun in the Miami area a high average annual water table existed almost to the shore line so that springs of fresh water flowed at the foot of Silver Bluff and little or not salt water was present in the formations containing water under water table conditions. This was because these rocks had been thoroughly flushed during times of the late Pleistocene low-level seas, and salt water had never been able to encroach in the face of the high fresh water levels that have existd in the area since the Recent rise to present day sea level. (2) The lowering of fresh-water head in the Miami area by the effective drainage of the Coastal Ridge, starting about

1910, has allowed a wedge of salt water to move inland at depth in the aquifer. (3) This wedge has moved in farthest and most rapidly in the coastal area of which Silver Bluff is a part because of the more effective drainage provided there by the Miami, Tamiami and Coral Gables Canals, which almost surround it. (4) This salt wedge probably will continue to move inland, interrupted by periods of high water table conditions, and probably will gradually contaminate new areas. (5) This inland movement may continue until the wedge reaches a line determined by the average height of the water table, where the weight of fresh water will force salt water to the bottom of the permeable aquifer. This height will probably be about 2½ feet (unless it is somewhat modified by a depressive force acting upon the salt-water wedge as the fresh ground water flows up over it). (6) This inland movement of the salt wedge will in any case be slow, and time remains for effective means to be put into effect to combat its further encroachment. (7) A very large aggregate quantity of potable ground water exists in the Miami area, sufficient for any foreseen increase in population, since a strip only one foot wide (north-south) extending 29 miles inland (east-west) contains over 15 million gallons of ground water. The principal part of this ground water reservoir lies in the area west of the salt-threatened zone, and comprises one of the most valuable natural assets of Dade County and Miami. It should be protected by effective controls placed in the drainage canals somewhere east and southeast of the present well field.

It would appear that, for any coastal area, the significant factors to be considered in determining the salt water-fresh water relationship will be found in:

(1) Determination of pertinent antecedent conditions, such as the cutting of drainage canals, installation of dikes, dams, or other water control structures, and the estimated conditions in the area before man-made changes occurred.

(2) Determination of the nature and extent of the aquifers. This involves geologic studies of structure, stratigraphy, lithology, and permeability, and requires test well drilling and pumping tests.

(3) Determination of the altitude of the average annual water table in feet above mean sea level and the construction of water table maps showing directions of movement of ground water.

(4) Study of the rainfall record in the area so that the sampling procedures may be adopted that will assure valid water samples taken at a time when the water table will be fairly stable.

(5) Determination of the specific gravity of normal ground water and of contaminating salt water, and the application of a suitable ratio to height of the water table based on these specific gravities.

MIAMI, FLA.,
July 19, 1944.

THE PERENNIAL YIELD OF ARTESIAN WATER IN THE COASTAL AREA OF GEORGIA AND NORTH-EASTERN FLORIDA.[1]

H. H. COOPER, JR. AND M. A. WARREN.

ABSTRACT.

Heavy withdrawal of artesian water in this area has created large cones of depression at Savannah and Fernandina and smaller cones at Jacksonville and Brunswick. If a substantial amount of water is being removed from storage in the formation, the cone of depression will continue to enlarge with no increase in withdrawal; otherwise it may be approximately stable. The coefficients of storage of the artesian limestones indicate whether it is likely that a large part of the withdrawal is coming from storage.

The results of pumping tests indicate that the coefficient of storage is about .00040 at Savannah, about .00025 at Fernandina, and about .00030 at Jacksonville. If these coefficients are representative, the water levels will become approximately stable within a few months, or a few years at most, after the rate of withdrawal becomes stable.

Large additional supplies of artesian water may be developed in most parts of the area providing new well fields are located at sufficient distances from existing ones and the lower parts of the water-bearing limestones are not developed too extensively. The present withdrawal at Savannah may ultimately cause salty water to move toward the well fields, but the movement would be slow enough to permit an orderly development of supplies of artesian water in areas west of Savannah.

CONTENTS.

[1] Published with the permission of the Director of the Geological Survey, United States Department of Interior; the Director of the Florida Geological Survey; and the Director of the Georgia Department of Mines, Mining and Geology. Presented before the Society of Economical Geologists, New York, Feb. 23, 1944.

INTRODUCTION.

THIS paper discusses some of the factors that relate to the yield of artesian water in the five coastal counties of Georgia and the two northernmost coastal counties of northeastern Florida. The rate of withdrawal of artesian water in this area is already large and is still increasing. As a part of the investigations by the Geological Survey, studies are being made to determine whether the rates of withdrawal exceed the perennial yield at places where the withdrawal is heaviest.

The investigations are under the direction of Mr. O. E. Meinzer, Geologist in charge of the Division of Ground Water, and Mr. V. T. Stringfield, of the Federal Geological Survey. The investigations in Georgia are in cooperation with the Georgia Division of Mines, Mining and Geology, and those in Florida, with the Florida Geological Survey. The writers are indebted to Mr. Herman Gunter, Director of the Florida Geological Survey, and Captain Garland Peyton, Director of the Georgia Department of Mines, Mining and Geology, for their cooperation and advice. Also, the writers are grateful to the many officials of cities and industries who made their wells available for pumping tests, and who otherwise gave freely of their time in making the tests possible.

GEOLOGY.

The Ocala limestone of Eocene age and some of the permeable Eocene limestones that immediately underlie the Ocala are the principal source of water in the area. In addition to these, a limestone of Oligocene age, which overlies the Ocala in some of the area, may be an important source of water. As these artesian formations are closely related hydrologically, they will be treated as a unit in this paper.

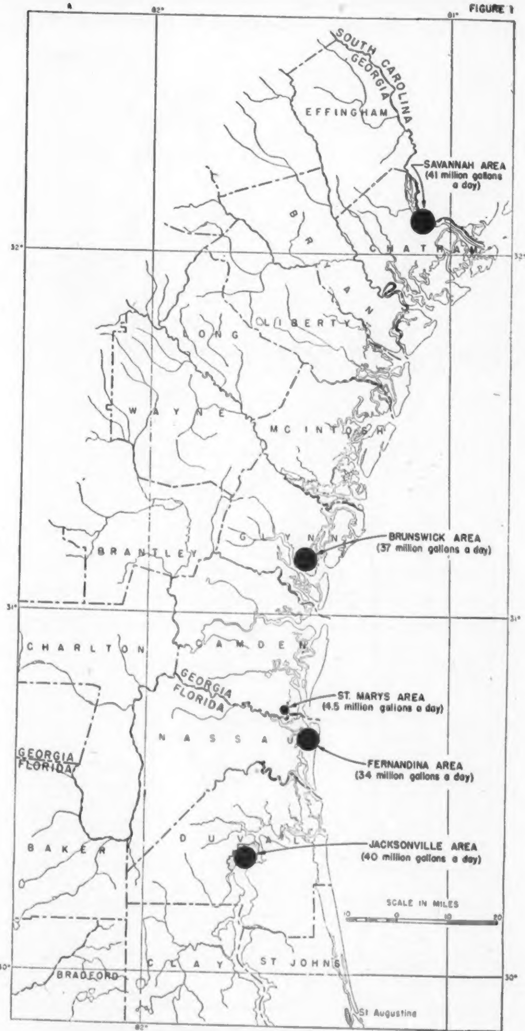
In the coastal area of Georgia and northeastern Florida the artesian formations dip in general toward the coast. The depth below sea level to the top of these formations ranges from about 200 feet at Savannah to 500 feet at Brunswick and 550 feet at Jacksonville and Fernandina. The total thickness of the permeable limestones at Savannah is about 750 feet. At Jacksonville the deepest wells penetrate about 800 feet of permeable limestones, but the total thickness may be much greater. The Ocala limestone crops out, or is near the surface, in an irregular belt which extends southwestward from Twiggs County, in central Georgia, into Alabama and Florida. In the vicinity of Twiggs County the Ocala grades into the less permeable Barnwell sand, of Eocene age, which crops out in a belt extending northeasterly into South Carolina.

The artesian formations are overlain throughout the area by the relatively impervious Hawthorn formation, of Miocene age, which prevents or retards the upward flow of artesian water.

WITHDRAWAL OF WATER.

The withdrawal of artesian water in the area first began between 1880 and 1890, when the first wells were developed, and has been increasing

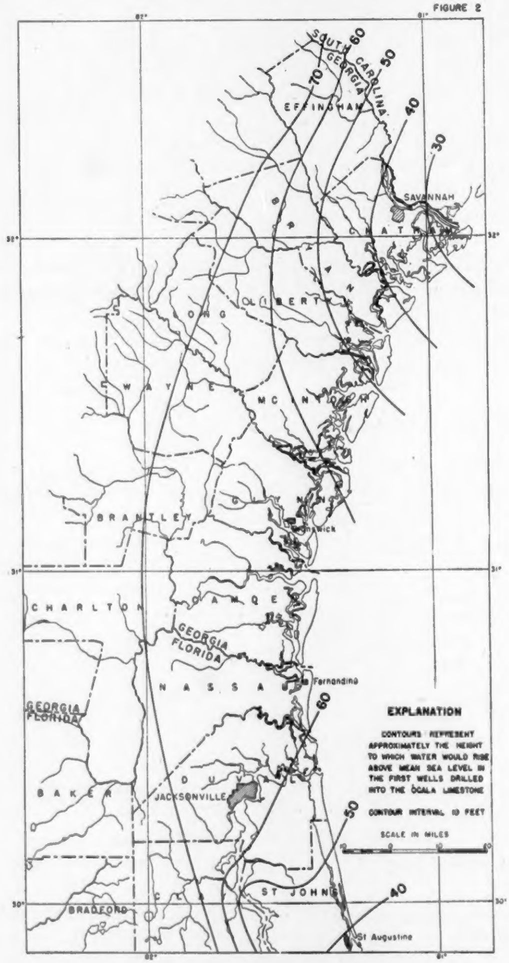
FIGURE 1



PRINCIPAL AREAS OF WITHDRAWAL OF ARTESIAN WATER
1943

steadily ever since. It is estimated that at least 200 million gallons a day are now being drawn from artesian wells in the area. About three-fourths of this is being drawn in the vicinities of Savannah, Brunswick, Fernandina, and

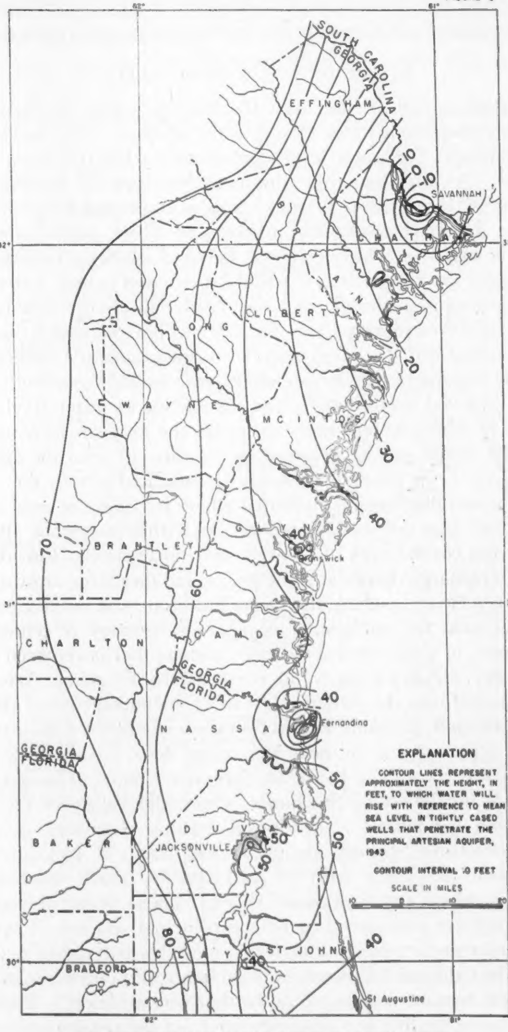
FIGURE 2



MAP REPRESENTING ORIGINAL PIEZOMETRIC SURFACE OF ARTESIAN WATER (PRIOR TO ABOUT 1880)

Jacksonville. The rates of withdrawal of water at these places, and at St. Marys, Georgia, are represented in Fig. 1. Fig. 2 shows the piezometric surface as it was before any artesian wells were developed. The withdrawal

FIGURE 3



MAP REPRESENTING PIEZOMETRIC SURFACE OF ARTESIAN. WATER
1943

of water has now created large cones of depression in the piezometric surface at Savannah and Fernandina, as indicated in Fig. 3. Relatively shallow cones of depression have been created at Brunswick and Jacksonville.

SOURCE OF WATER FROM WELLS.

For a certain period of time after the discharge from wells begins, all of the discharge comes from water stored in the aquifer. The removal of water from storage lowers the water levels and creates what is known as the cone of depression. As the discharge continues, the cone of depression deepens and broadens. Ultimately, if the discharge is continued long enough, water levels will be lowered appreciably in areas in which water is entering the aquifer and in areas in which water is being discharged naturally. Under favorable conditions the recharge will be increased when water levels are lowered in an area of recharge, and the natural discharge will be decreased when they are lowered in an area of discharge. The increase in recharge plus the decrease in natural discharge may be termed *salvage*. When, and only when, the rate of salvage equals the rate of withdrawal from wells, water will no longer be removed from storage, and the decline of water levels will cease.

The areas in which water enters or leaves the artesian formations are indicated by the shape of the piezometric surface in Florida and southern Georgia (Fig. 4). In general, recharge is indicated where the piezometric surface is high, and discharge is indicated where it is low, Several areas of recharge and discharge are considered to be within range of the cones of depression in the coastal area of Georgia and northeastern Florida. One of these, in which recharge occurs at some places and discharge at others, extends diagonally across Georgia where the Ocala limestone and other Eocene formations are at or near the surface. One area of recharge is centered around Lowndes County, in south-central Georgia, and another is centered around the southwest corner of Clay County, in northeastern Florida. Artesian water is being discharged into the Atlantic Ocean at an undetermined distance offshore from Savannah, probably within 50 miles, where the top of the artesian formations is apparently at or near the ocean floor. Also, it is being discharged along the Savannah River in Screvens County, Georgia, about 40 miles and more northwest of Savannah, where the valley of the river cuts into the artesian formations. In Florida, natural discharge occurs in the vicinity of Green Cove Springs, about 25 miles south of Jacksonville. At a distance of about 85 miles west of Jacksonville, much discharge occurs through springs along the Suwannee River. These areas of recharge and natural discharge are considered to be the principal sources of salvage, that is, they are the areas in which water levels must be lowered in order for the withdrawal to be balanced by increases in recharge and decreases in discharge. Other such areas may be discovered on further investigation. Those areas of recharge and discharge that are relatively far from the coastal area of Georgia and northeastern Florida are not considered here, because practically all the salvage would apparently be derived from areas that are closer. Other major areas of discharge are at distances of 75 miles and more south and southwest of Jacksonville, where the Ocala limestone is at or near the surface in Marion and Volusia Counties. In this area numerous springs discharge large quantities of artesian water.

In considering whether the rate of withdrawal in an area can be continued indefinitely, it is important to know whether the withdrawal is balanced by

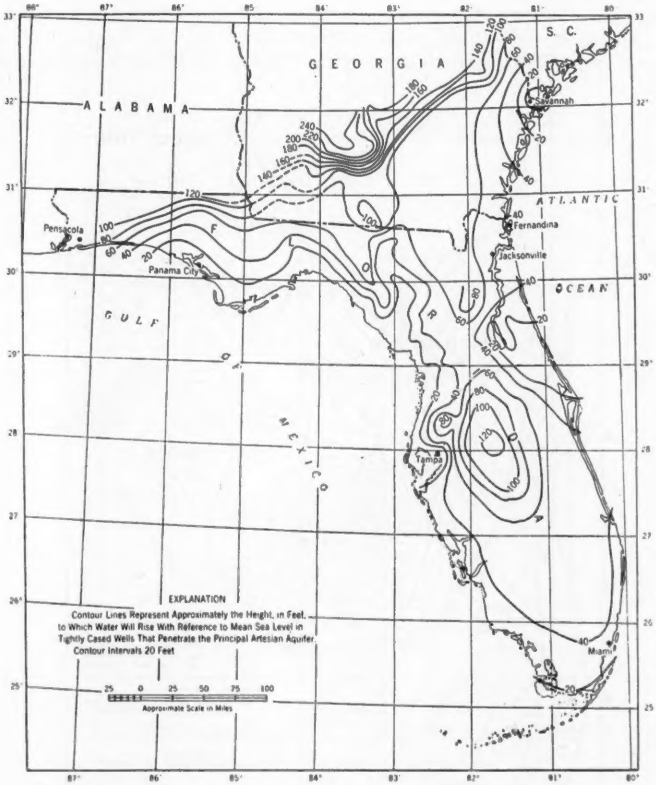


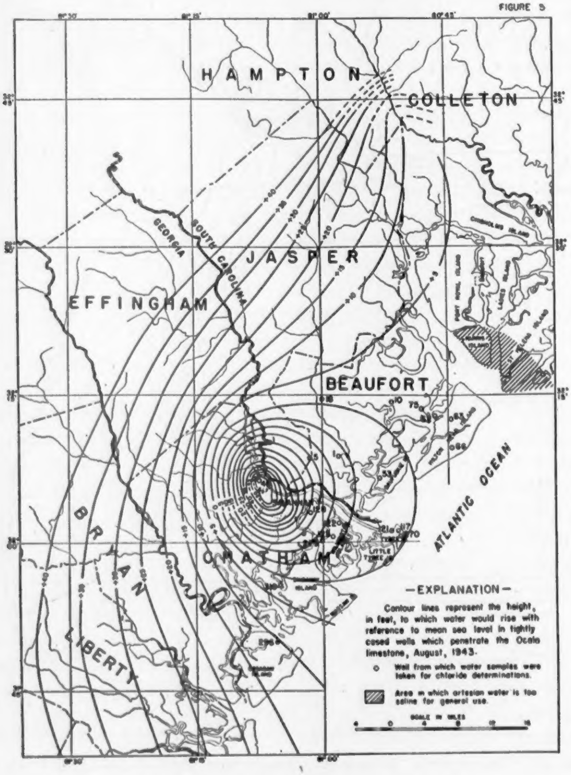
FIG. 4. Piezometric surface in Florida and part of Georgia, 1943.

salvage, or whether a substantial part of it is coming from a gradually diminishing storage. If a substantial part of the withdrawal is coming from storage, the cone of depression will continue to grow, although the rate of withdrawal is not increased.

SALT-WATER ENCROACHMENT.

At Savannah any further growth of the cone of depression may cause saline water to move toward the well field. Fig. 5 shows in more detail the present extent of this cone. In an area about 30 miles northeast and east of Savannah, represented by cross-hatching in Fig. 5, the artesian water is somewhat saline. Salty water may even now be moving toward the Savannah well fields. However, it appears that under present conditions any such movement would be very slow, probably not more than a few hundred feet a year.

FIGURE 5

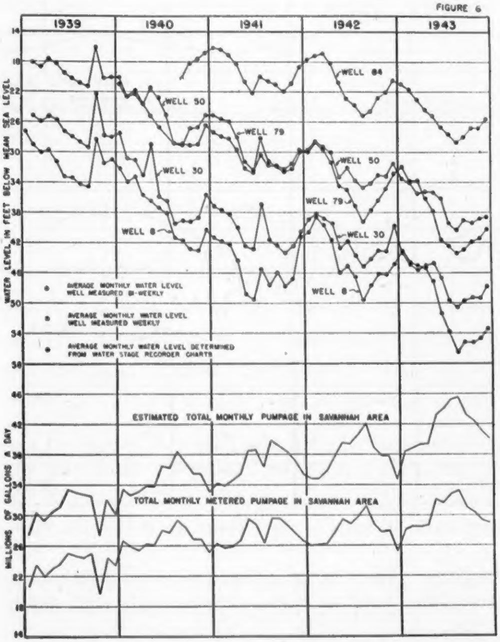


MAP REPRESENTING PIEZOMETRIC SURFACE OF ARTESIAN WATER, SAVANNAH AND VICINITY

At Fernandina, where heavily pumped wells are located very near the coast, the relatively impervious Hawthorn formation has apparently prevented sea water from entering the artesian formations. Presumably the Hawthorn is continuous for a considerable distance offshore from Fernandina, but there is no information to indicate definitely that this is true. Therefore, the possibility that the cone may extend to places where sea water will seep through the Hawthorn into the artesian formations cannot be dismissed altogether.

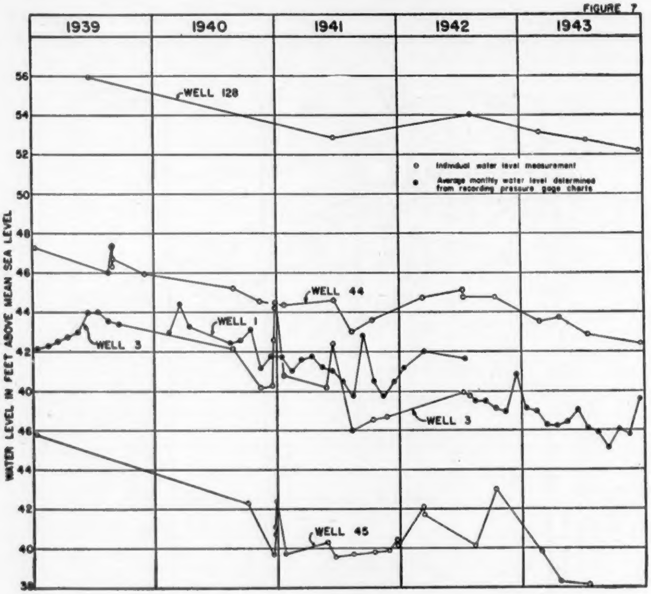
Apparently there is comparatively little danger that salty water will move laterally into Brunswick and Jacksonville from areas in which artesian water is saline, or from areas in which saline water may enter the artesian formations from the sea. It is more likely that any salting in the water-producing formations at Brunswick and Jacksonville would be a result of upward movement of saline water from horizons that underlie the water-producing formations. Records of deep wells indicate that all of the area is underlain with formations containing saline water. At Hilliard, in Nassau County, Florida,

FIGURE 6



WATER LEVELS IN WELLS IN THE VICINITY OF SAVANNAH, GEORGIA

water with a chloride content of 33,600 parts per million was penetrated at a depth of 2,200 feet, and water with a chloride content of 60,200 parts per million was penetrated at 4,500 feet by an oil test well. If the formations were isotropic and permeable down to the depth at which saline water is present, the lowering of water levels at Savannah, Brunswick, Fernandina, or Jacksonville would already have permitted saline water to move upward into the water-producing formations. Information available at the present time indicates that saline water cannot move upward into the water-producing formations at Jacksonville unless there is extensive development of deeper wells, or unless the cone of depression deepens and broadens considerably, because relatively impervious layers of limestone are preserving the artesian pressure in limestones that lie between the water-producing formations and the saline water. The same condition presumably exists at Fernandina. At Brunswick, conditions may not be comparable to those at Jacksonville because water with a chloride content of 146 parts per million was penetrated in a



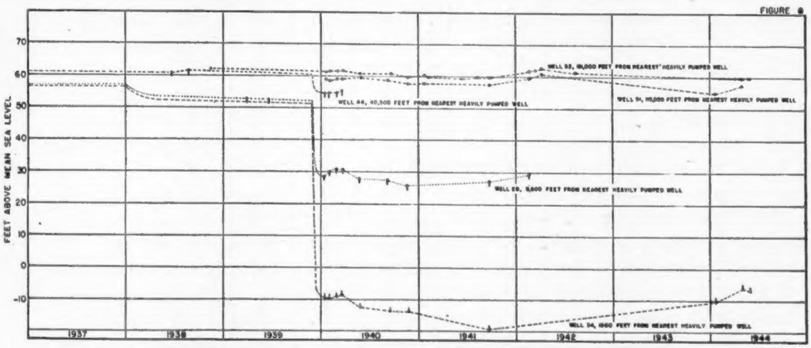
Water levels in wells in the vicinity of Brunswick, Georgia.

well 1,050 feet deep. There is no information to indicate, however, that the chloride content of the water at Brunswick increases with depth.

WATER LEVELS.

Water levels in this area have declined gradually since the development of wells first began. Figs. 6, 7, 8, and 9 show the water levels during recent years in wells in the vicinities of Savannah, Brunswick, Fernandina, and Jacksonville respectively. The rates of withdrawal at Savannah and Brunswick increased more or less uniformly during the period for which water-level declines are shown. The variations in the rate of withdrawal at Savannah are shown in Fig. 6. The rate of withdrawal at Brunswick increased from about 31,000,000 gallons a day in 1939 to about 37,000,000 gallons a day in 1943. At Jacksonville the rate of withdrawal undoubtedly increased several million gallons a day between 1930 and 1944, but information regarding the rate prior to 1942 is incomplete. At Fernandina the rate of withdrawal was less than 0.5 million gallons a day prior to 1938, about 3.5 million gallons a day between January 1, 1938, and December 1, 1939, and about 34 million gallons a day since December 1, 1939.

It is readily apparent that practically all of the decline at Fernandina during recent years is a result of increases in the rate of withdrawal. It is also apparent that at least part of the decline at Savannah and Brunswick is due to the increases in the rates of withdrawal. However, a study of the hydrographs does not reveal whether the water levels would continue to decline gradually for a long period of time even though there were no increases in the rates of withdrawal, that is, whether a substantial part of the withdrawal



WATER LEVELS IN WELLS IN THE VICINITY OF FERNANDINA, FLORIDA

is coming from a storage which will ultimately be consumed. Analyses involving the capacities of the formations to transmit and store water provide a means for determining, roughly, whether this condition exists.

STORAGE AND TRANSMISSIBILITY.

The rate and extent of decline of water levels in the vicinity of a pumped well depend on the capacities of the aquifer to transmit water under a hydraulic gradient and to release water from storage when the water level declines. A measure of the capacity of an aquifer to transmit water is the *coefficient of transmissibility,* which is the number of gallons of water that will be transmitted each day through a vertical cross section of the aquifer having a width of one foot and a height equal to that of the aquifer, under a 100 per cent hydraulic gradient. A measure of the capacity of the aquifer to release water from storage is the *coefficient of storage,* which is the volume of water in cubic feet that will be released in a vertical column of the aquifer having a base of one foot and a height equal to that of the aquifer, when the water level declines one foot. The water that is released from storage in an artesian aquifer comes partly from an expansion of the confined water, partly from a compression of the aquifer, and partly from a release of water from contiguous beds.

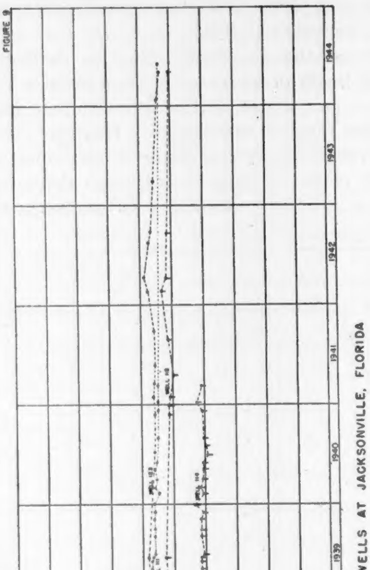


FIGURE 9
WATER LEVELS IN WELLS AT JACKSONVILLE, FLORIDA
FEET ABOVE MEAN SEA LEVEL
NO MEASUREMENTS 1932-1936
1930
1931
1937
1938
1939
1940
1941
1942
1943
1944

Pumping tests to determine the coefficients of transmissibility and storage have been made at several places in the coastal area of Georgia and northeastern Florida. Determinations of the coefficients from the results of these tests are shown in Table 1. The methods used to determine the coefficients are: the non-equilibrium method, the Theis recovery method, the Thiem method, and the gradient method. Discussions of these methods, their fundamental principles, and the assumptions on which they are based are given in a paper by Wenzel.[2]

All four methods can be used to determine the coefficient of transmissibility, but only the non-equilibrium method can be used to determine the coefficient of storage. The information necessary for application of the non-equilibrium method was not obtainable during many of the tests, so that only a few determinations of the coefficient of storage have been made.

The figures for the coefficients of transmissibility and storage shown in Table 1 are widely disparate. The disparity may be due principally to actual variations in the coefficients from one place to another, but it is undoubtedly due also, at least in part, to differences between actual conditions and the assumptions on which the methods for determining the coefficients are based. All of the methods assume (1) that the aquifer is hydrologically homogeneous and isotropic throughout, and that the wells penetrate its entire thickness, (2) that the rate of flow through the aquifer is directly proportional to the hydraulic gradient, (3) that the aquifer is bounded above and below by impervious formations which prevent any water from entering or leaving it except through wells, and (4) that the transmissibility is constant throughout the area in which water levels are affected during the discharge of the well. The non-equilibrium and recovery methods assume further (5) that the storage coefficient is constant and (6) that the water is released from storage instantaneously as the water level declines. The extent to which the characteristics of the artesian formations in the coastal area of Georgia and northeastern Florida conform with these assumptions will be discussed in the following paragraphs.

(1) In northeastern Florida, and probably in other parts of the area as well, the artesian formations are composed of layers of permeable limestone that are sealed off from one another, at least locally, by more or less continuous layers of relatively impervious limestone in such a way that a well penetrating only the the upper permeable layers will receive little or no water directly from the lower ones. Thus, coefficients of transmissibility and storage computed from tests on wells that penetrate only the upper part of the aquifer are probably smaller than the true coefficients of the aquifer as a whole. Probably few of the wells on which tests were made penetrate all of the permeable limestone, although some of the wells at Savannah penetrate most of it.

In the vicinity of Jacksonville many wells have penetrated open caverns in the limestones. Any caverns where a test is made would cause water to flow along indeterminable tortuous paths instead of along straight lines radi-

[2] Wenzel, L. K.: Methods for determining permeability of water-bearing materials. U. S. Geol. Surv. W.S.P. 887, 1942.

ating from the discharging wells. This would vitiate the results of the test considerably. A test on a well that penetrates a continuous cavern a few inches or more in diameter will obviously give misleading results. Possibly some of the tests in the area are affected by cavernous conditions.

The unusually large transmissibility coefficient of 1,000,000, determined from the test on well 161 near Yukon, Duval County, Florida, (see number 12, Table 1) may be due to caverns in the limestone. One well in the vicinity of Yukon, which is reported to have penetrated a large cavern immediately below the top of the Ocala limestone, yielded 6,500 gallons a minute by natural flow.

(2) In limestones that contain many ramifying solution passages the flow of water in the vicinity of a discharging well may be turbulent, so that the rate of flow would not be directly proportional to the hydraulic gradient. It is probable that this condition exists in some parts of the area.

(3) In some places artesian water may be leaking upward from the limestone formations into the overlying Hawthorn formation. Such leakage apparently occurs in the vicinity of Green Cove Springs, in Clay County, Florida, where the withdrawal from wells and the small flow of the Spring are not large enough to account for the large depression in the piezometric surface in that area. A test in an area in which such leakage occurs would give unreliable results because part of the discharge from the well would be balanced by a decrease in the rate of leakage. This would cause the computed coefficients of transmissibility and storage to be too large.

(4, 5) The coefficients of transmissibility and storage undoubtedly range widely over the area. In a test of several days duration, or even one of only a few hours duration, changes in water levels produced by changes in the rate of discharge from the test wells may extend to places in which the coefficients are different. In using the non-equilibrium and recovery methods the data obtained during the first part of such a test might give reliable indications of the coefficients in the vicinity of the tested wells, but those obtained during the latter part of the test would not. The test near Savannah (see number 1, Table 1) lasted eleven days. During this time the normal daily discharge from the wells was decreased from 14.7 million gallons to 2.08 million gallons, and measurements of water levels were made in four wells in the vicinity of the discharging wells. The recovery of water levels during the latter part of the test was slower than it should have been according to theory, indicating that the effect of the decrease in withdrawal may have extended to areas in which the characteristics of the artesian formations are different from those in the vicinity of the wells used for the test. Therefore the measurements made during the early part of the test were given more weight in determining the coefficients of transmissibility and storage by the non-equilibrium method.

(6) When water levels decline the release of water from any beds of clay contiguous to the aquifer, or from any included layers of limestone of low permeability, would not be instantaneous. Slow release of water in the vicinity of a discharging well would cause water levels to decline more rapidly at first and more slowly later. The effect of slow release on the determina-

tion of the coefficients of transmissibility and storage will be relatively small if the determinations are based on changes in water levels at a relatively long distance from the discharging well. The storage coefficients determined from observed recoveries in wells 74, 28, 30, and 50 during the test at Savannah (see number 1, Table 1) range from .00017 to .00041. These coefficients increase as the distance from the observed well to the discharging wells increases, indicating slow release of storage. Wells 74, 28, 30, and 50 are respectively 3,000, 5,400, 5,900, and 7,300 feet from the nearest pumped wells. A determination based on the recovery of the water level in a well 30,000 feet from the pumped wells indicates that the coefficient of storage in the vicinity of Savannah may be higher than .00041, possibly as high as .001; but as this recovery was only about 1.6 feet, it may have been modified enough by fluctuations from natural causes to invalidate the determination.

PRACTICAL APPLICATION OF TRANSMISSIBILITY AND STORAGE COEFFICIENTS

In order to determine whether it is likely that an appreciable lowering of water levels due to withdrawal has extended to areas of recharge and areas of discharge, and thus, whether the withdrawal may be balanced largely by salvage, drawdowns that would be created in an ideal aquifer of infinite areal extent by a discharge of 30 million gallons a day from one well have been computed by means of the Theis non-equilibrium formula.[3] Figs. 10, 11, and 13 represent computed drawdowns for several lengths of time after discharge is begun, plotted against the distances from the discharging well. These are profiles of the cone of depression with distances shown on a logarithmic scale. They demonstrate the manner in which the cones of depression will enlarge while all the withdrawal is coming from storage in the aquifer. Over the distance in which these profiles plot as straight lines, the shape of the cone of depression is essentially stable and water levels at all places are declining at essentially an equal rate.

In computing the drawdowns it was assumed that all of the discharge was from one well, whereas at the areas considered, water is drawn from widely scattered wells. The differences due to this assumption would be large for short distances, but they would be slight or negligible for long distances.

The rate of growth of the cone of depression is dependent on the rate of withdrawal, the transmissibility coefficient, and the storage coefficient. After the withdrawal is balanced entirely by salvage, and water levels are approximately stable, the breadth and depth of the cone will be dependent on (1) the rate of withdrawal, (2) the transmissibility, and (3) the relative location of the wells with respect to areas of recharge and discharge.

Where the distances from the areas of withdrawal to areas of recharge and discharge are known, the length of time that will be required for the water levels to be lowered appreciably over these distances may be determined with an accuracy that is commensurate with the extent to which the characteris-

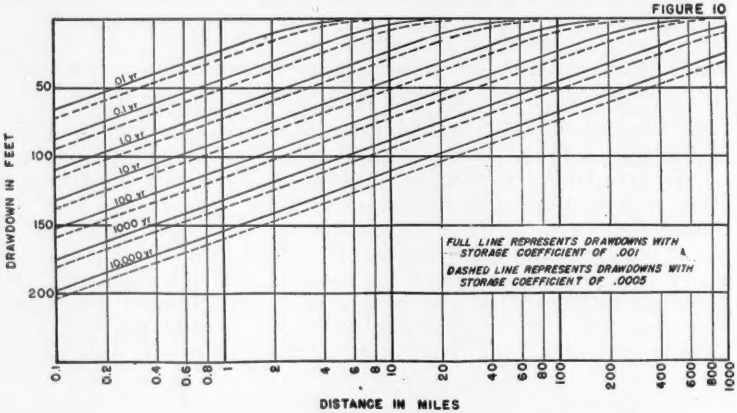
[3] Theis, C. V.: The relation between the covering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. Am. Geophys. Union, Trans.: 1935, pp. 519–524.

tics of the aquifer conform with the simplifying assumptions. These assumptions are the same as those on which the methods for determining the transmissibility and storage coefficients are based.

Savannah

Fig. 10 shows the growth of the cone of depression in an ideal aquifer having transmissibility and storage coefficients approximately equal to those determined for the Savannah area. The distance from the approximate center of the cone of depression at Savannah to the area of natural discharge in Screvens County is about 40 miles. An inspection of Fig. 10 reveals that in an ideal aquifer water levels would be lowered appreciably over a distance

FIGURE 10



DRAWDOWN IN AN IDEAL AQUIFER OF INFINITE AREAL EXTENT CAUSED BY CONTINUOUS DISCHARGE OF A WELL AT A RATE OF 30 MILLION GALLONS A DAY

Storage coefficient, .001 and .0005; Transmissibility coefficient 250,000

of 40 miles within one year after discharge began. If the potential rate of salvage within a distance of 40 miles is equal to the withdrawal, the cone of depression will gradually change in shape and finally become stable after it extends that distance. After the cone extends to an area of potential salvage, a long period of time will elapse before water levels in the area are lowered enough for the rate of salvage to equal the rate of withdrawal. Thus, although a measurable lowering of water levels caused by pumping at Savannah may have extended into an area of potential salvage, water levels might continue to decline for several years. Probably most of the withdrawal at Savannah is now balanced by salvage, but whether all of it is so balanced cannot be determined with the information available at this time.

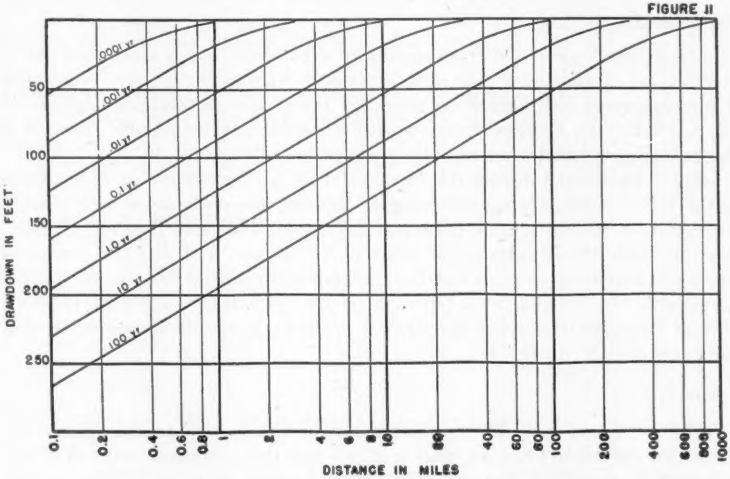
Brunswick

The transmissibility coefficient in the Brunswick area has been determined approximately to be between 750,000 and 1,000,000. The cone of depression at Brunswick is shallow for the large withdrawal, which indicates that either the transmissibility coefficient or the storage coefficient is large. If the storage coefficient is small, and the shallowness of the cone of depression is due solely to the large transmissibility, it is likely that the withdrawal is already balanced largely, perhaps entirely, by salvage. As yet, no determination of the storage coefficient at Brunswick has been made. When determinations of both coefficients are available, the condition at Brunswick may be analyzed.

Fernandina

Fig. 11 shows the expansion of the cone of depression with coefficients approximately equal to those determined for the Fernandina area.

FIGURE 11



DRAWDOWN IN AN IDEAL AQUIFER OF INFINITE AREAL EXTENT CAUSED BY CONTINUOUS DISCHARGE OF A WELL AT A RATE OF 30 MILLION GALLONS A DAY

Storage coefficient, .0002, Transmissibility coefficient, 155,000

Determinations of the transmissibility coefficient at Fernandina based on a pumping test of short duration range from 151,000 to 159,000 (see number 5, Table 1). As the wells tested penetrate only about 550 feet into the artesian formations, whereas the total thickness is probably much greater, these figures may not represent the transmissibility of the aquifer as a whole. Approximate computations based on the shape of the large cone of depression around Fernandina indicate that the transmissibility coefficient may be about 190,000 (see number 6, Table 1). In computing the curves shown in Fig. 11, however, the coefficients determined from the pumping tests are assumed to be more nearly representative; hence a transmissibility cofficient of 155,000 and a storage coefficient of .0002 have been used.

In order for the withdrawal at Fernandina to be balanced by salvage, the cone of depression apparently must extend into the area of discharge in the vicinity of Green Cove Springs, into the recharge area near the southwest corner of Clay County, and possibly into some of the recharge and discharge areas that are farther away. If, however, there were any leakage from the aquifer in areas much closer to Fernandina, the decrease in that leakage, which would be caused by the lowering of the artesian pressure, would balance some of the withdrawal. The discharge area at Green Cove Springs is about 50 miles from Fernandina, and the recharge area at the southwest corner of Clay County is about 70 miles away. Fig. 11 indicates that in an ideal aquifer having transmissibility and storage coefficients of 155,000 and .0002 respectively, water levels would be lowered as far as these areas by the end of one year.

Jacksonville

Determinations of the transmissibility coefficient in the vicinity of Jacksonville are so disparate that it is impossible to select, with any reasonable assurance, one which represents generally the water transmitting capacity of the aquifer. An average figure probably would not be reliable, though it might be more so than one of the highest or lowest.

Fig. 9 shows that during the 13 years of record the decline of water levels in the Jacksonville area was very slight, although the withdrawal undoubtedly increased by several million gallons a day. This indicates that for all practical purposes the withdrawal is balanced by salvage, and that the source of salvage is relatively close or else the transmissibility in the area is very large. In general, the outlook for a perennial supply of artesian water at Jacksonville at the present rate of withdrawal, or with moderate increases in that rate, appears very favorable.

Limitations

The computed drawdowns represented in the figures in this paper are those that would occur in an ideal aquifer—one that conforms with all of the assumptions on which the non-equilibrium formula is based. None of the aquifers that occur naturally are ideal in this sense, although some are more nearly so than others. Other investigations have demonstrated that the effect of ground-water developments in those aquifers that conform closely with ideal conditions may be foretold with a fair degree of accuracy. Some very good results have been obtained for aquifers consisting mostly of sand, but the applicability of existing formulas to limestone formations that contain ramifying solution channels is yet to be demonstrated.

It may be expected that determinations of transmissibility and storage coefficients that will be made in the future will supplement and verify, or refute, those already made. Also, close observation of extensive recovery and decline of water levels that occur when heavy pumping, such as that at some of the large paper mills in this area, is stopped for several days and then started again, will serve to test the validity of determinations based on tests that utilize individual wells discharging relatively small quantities of water.

As the transmissibility and storage coefficients range widely over the area, a precise forecast of drawdowns by use of the non-equilibrium formula is not

TABLE I.

COEFFICIENTS OF TRANSMISSIBILITY AND STORAGE OF THE LIMESTONE AQUIFER.

Reference Number	Location of Test	Well Number		Coefficient of Transmissibility				Coefficient of storage
		Discharging	Observed	By non-equilibrium method	By recovery method	By Thiem method	By gradient method	
(1)	Union Bag and Paper Co., Savannah, Georgia (Chatham County)	36, 37, 38, 39, and 40	28	280,000	—	—	—	0.00026
			30	220,000	—	—	—	0.00040
			50	270,000	—	—	—	0.00041
			74	260,000	—	—	—	0.00017
			30 and 74	—	—	210,000	—	—
(2)	Savannah, Georgia (Chatham County)	Many	Many	—	—	—	222,000	—
(3)	Hinesville, Georgia (Liberty County)	161	161	—	780,000	—	—	—
(4)	St. Marys, Georgia (Camden County)	155	3, 18, 19 and 39	—	—	118,000	—	—
(5)	Rayonier, Inc., Fernandina, Florida (Nassau County)	39	39, 40, 41, 42, and 43	151,000	154,000	159,000	—	0.00025
(6)	Fernandina, Florida (Nassau County)	Many	Many	—	—	—	190,000	—
(7)	Fairfax Ave. and 20th St., Jacksonville, Florida (Duval County)	52	52	—	170,000	—	—	—
(8)	River Oak Road and F.E.C.R.R., Jacksonville, Florida (Duval County)	54	54 and 54-A	125,000	105,000	—	—	0.00029
(9)	Baltic and Oxford Sts., Jacksonville, Florida (Duval County)	115	115	—	54,000	—	—	—
(10)	Post and Dancy Sts., Jacksonville, Florida (Duval County)	118	118	—	160,000	—	—	—
(11)	Woodstock Park, Jacksonville, Florida (Duval County)	123	123	—	86,000	—	—	—
(12)	Yukon, 8 miles south of Jacksonville, Florida (Duval County)	161	161	1,000,000	—	—	—	—
(13)	20 miles southwest of Jacksonville, Florida (Duval County)	222	222-A	190,000	—	—	—	0.00035

possible. However, if the coefficients are approximately the same over a substantial distance in every direction from the discharging wells, computed drawdowns for short distances should be fairly dependable.

CONCLUSIONS.

In view of the many differences between actual conditions and the necessary simplifying assumptions, any conclusions regarding the permanency of water supplies in the area must be made with considerable reservation. However, it appears probable that water levels at Fernandina or Jacksonville will become approximately stable within a few months after each increase in the rate of withdrawal, and that those at Savannah will approach stability within one to ten years.

There is no information to indicate that the present rates of withdrawal at Jacksonville and Fernandina cannot be continued indefinitely. Possibly much larger quantities of water may be withdrawn at either of these places with no undesirable consequences if new well fields are located at ample distances from the existing ones, and if deeper water-bearing formations are developed only with considerable caution and careful control.

The withdrawal at Savannah may ultimately cause salty water to move into the well fields. However, the movement would be slow enough to permit orderly and effective development of additional supplies of artesian water in the area west of Savannah where there is relatively little danger of salt-water encroachment.

SOME APPLICATIONS OF STRUCTURAL GEOLOGY TO MINING IN THE PACHUCA–REAL DEL MONTE AREA, PACHUCA SILVER DISTRICT, MEXICO.

C. L. THORNBURG.

THE following discussion is based on a type of vein structure rather common in Pachuca and adjacent districts and deals with the application of certain principles of structural geology to local problems of development and exploration. Detailed examination of vein structures, in conjunction with the application of these principles, has yielded practical results in so many instances that it has become a necessary part of routine geological work. Accumulated evidence indicates that a large number of the pre-mineral fractures must have been formed as a result of what may be described as a normal fault type of rupturing. This evidence has become so abundant and widespread that the writer is inclined to regard the dominant type of pre-mineral fracturing in the Pachuca region as normal faulting. The object of this discussion is to show why fractures of this type are believed to be common and to illustrate how the interpretation of their nature is applied in our work. It is not intended to explain in detail the extensive and complicated fracture systems of the entire region. The main structural principle involved in the following cases finds its chief use in providing a foreknowledge of conditions along a known vein zone, being of doubtful value in wholly unknown ground. But, even though this application may be limited to local problems, it has been of great importance when evaluated in terms of ore increments derived from branch veins and splits.

GEOLOGICAL SUMMARY.

This district is an outstanding example of those Tertiary vein deposits which have yielded a large part of the world's production of silver. The mines are situated in a mountain range which was built up as the result of a long period of successive volcanic eruptions. The eruptive rocks, which are largely andesitic, attain a thickness of perhaps more than 2,000 meters. Crustal adjustments which accompanied and followed the prolonged volcanic activity resulted in widespread fracturing and faulting. From the general geological sequence it may be inferred that as the underlying magma cooled, volcanic activity diminished and mineralizing solutions of locally varying intensity rose from depth and accomplished vein formation throughout the extensive fracture system.

In order to clarify the terminology used in this discussion, it should be explained that "normal fault rupture" is the term used in referring to the type of fracturing that takes place in the process of normal faulting or the settling of earth blocks due to gravitational force (Fig. 1). Compressive stress is the term used here in referring to the theory that the north-south fractures were formed and that transverse (northwesterly to east-west) fractures were squeezed open by east-west compression, which is not in accord with the conception of tensional rupturing presented here.

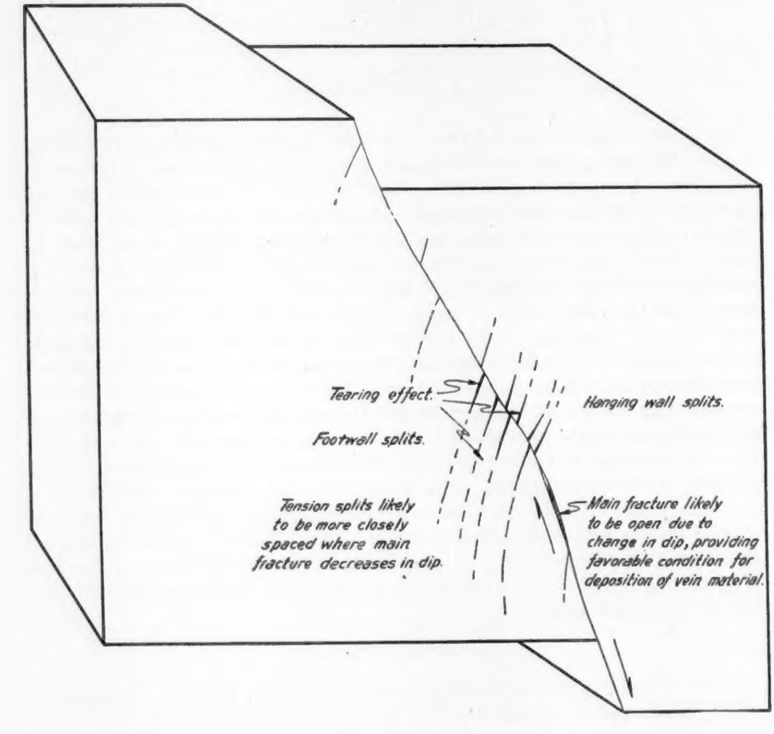


Fig. 1 - Idealized Block Diagram showing tensional effect related to normal fault type of rupturing.

TREND OF IDEAS REGARDING THE ORIGIN OF PRE-MINERAL FRACTURES.

Valuable contributions to the analytical study of local structural problems have been made by a number of earlier geologists. There has been some divergence of opinions, perhaps largely because the nature of Geological Department work has of necessity undergone changes from time to time and the development of different individual theories has been influenced by the type of work carried out during a given period. In the past it was most important that the Department obtain a regional picture of such features as stratigraphy and distribution of mineralization as well as structure. This earlier work contributed greatly to a geological knowledge of the district but, on the whole, it served as a basis for conclusions drawn from generalized rather than detailed information. A large-scale horizontal projection showing the main fractures of the Real del Monte area, including those that are poorly mineralized as well as the productive veins, suggests that the subregional pattern formed by the north-south and transverse veins might be the result of compressive stresses applied horizontally operating in a more or less horizontal plane. On the other hand, detailed data from individual fractures indicate that the dominant forces were essentially vertical. So it is that a generalized picture may suggest a concept which is inconsistent with local conditions. General information as well as details is needed, but the importance of attention to local details has become increasingly evident in more recent years. Stope mapping is now almost as regular a practice as mapping on levels, and it is usually in the stopes that the mechanics of fracturing can be more clearly inferred.

In April, 1929, L. Salazar Salinas, Director of the Geological Institute of Mexico, commissioned Ing. Manuel Santillán to study the mineral deposits of Pachuca and their relation to Miocene rocks. Ing. Santillán presented his report in May 1930.[1] Under the heading of Structural Geology, he comments on evidence that compressive stresses played an important part in the origin of the fractures, this evidence being the "rectangular" pattern formed by certain veins of Real del Monte. Santillán was not attempting to present a complete picture of the structural geology, but his reference is of interest in that it seems to reflect a theory under consideration at that time.

All of the recorded statements pertaining to the structural geology of the district are not readily available, but it is evident from private reports that, as geological studies proceeded, two distinct lines of thought were being expressed, namely, (1) that pre-mineral fracturing in general was caused by subsidence on a large scale, and (2) that the north-south fractures developed contemporaneously with concomitant transverse fractures as a result of compressive stress. Wisser expanded the latter theory in far greater detail than any previous geologist, and although the ideas set forth in his paper [2] are not in general accord with the type of rupturing explained here, the writer feels that Wisser's detailed discussion had a stimulating effect on the study of structural geology in this district.

Those holding the opinion that the pre-mineral fractures were formed by compressive, horizontal movements believe that the mineralization of the north-south and transverse fractures was contemporaneous; because this theory necessitates the assumption that the fractures of both systems were open to mineralization during the same period. But it is difficult to conceive of all

[1] Estudio Geológico del Mineral de Pachuca por Ing. Manuel Santillán, Mayo 1930.

[2] Formation of the north-south fractures of the Real del Monte area, Pachuca silver district, Mexico, by Edward Wisser. Transactions A. I. M. E., vol. 126, 1937.

of the transverse fractures in the heart of Real del Monte as having been open during the time that veins of the north-south system were formed. An outstanding feature of Real del Monte is that the vertical range of ore on the north-south veins is greater and much deeper than that of transverse veins right in the same general locality. Moreover, the difference in mineralogical characteristics between veins of the two systems is manifest, even though both types are highly siliceous. If the transverse fractures had been open to solutions at the same time the nearby north-south fractures were, one would expect them to have the same type of mineralization as the north-south veins, and to be mineralized over more or less the same vertical range. This disparity alone is an obstacle to the acceptance of the theory that the mineralized fractures were formed by horizontal compressive stress, and it should be pointed out, as a matter of constructive criticism, that the exponents of the compressive stress theory have not explained it.

When one undertakes the study of structure in this district he is confronted with two outstanding features which might seem to support the theory of compressive stress. First, there is the sub-rectangular pattern formed by the north-south and transverse veins in Real del Monte, and second, it is a fact that horizontal and low-angle striations are commonly found in the late gouge along transverse fractures throughout the district. It appears that these two features have strongly influenced those who maintain that the pre-mineral fractures were caused by compressive stress. As regards the first point, it has already been stated that local geological conditions do not substantiate the theory suggested by the Real del Monte pattern. In considering the significance of the second feature it is important to note that striations in the soft gouge record only a late horizontal post-mineral movement, which in places obscures the nature of the pre-mineral fracturing, but in itself provides no clue for interpreting the origin of the earlier mineralized fractures.

Steeply dipping hangingwall and footwall fractures which strike more or less parallel to the main inclined plane of normal movement are recognized here and elsewhere as common characteristics of the normal fault type of rupture of rock formations. These are parasitic branch fractures formed by tensional forces set up along and near the main plane of movement and they gradually diminish and fade out as they extend outward into the walls (Fig. 1). Numerous examples of this type of fracturing are found on the north-south, northwest, east-west and northeast veins of this district. It is evident that both the main fracture and the associated branches would provide openings for solutions during the process of mineralization. Additional evidence in favor of this conception of the mechanics of vein formation is provided in some places by mullions or grooves parallel to the dip of the main fracture, having been carved in its walls as a result of rock surfaces moving against each other. These grooves, having become filled with quartz during mineralization, are accurate indicators of the direction of movement. The fact that these quartz-lined grooves, parallel to the dip, are found in so many Pachuca and Real del Monte veins strengthens the interpretation of the fracture pattern described above, and in such cases the logical conclusion is that the pre-mineral movement was normal. When the quartz-lined grooves are obscured by post mineral gouge, the observer should look for other reliable guides as to the nature of pre-mineral movements, because if he gives undue importance to the orientation of striations in the soft gouge, which record only the latest movements, he might be led to an erroneous conclusion regarding the origin of the pre-mineral fracture.

Much was accomplished to facilitate the study of structural geology in this district as a result of the investigation by Dr. W. J. Mead in the summer of 1937. Discussions held underground and in the field proved to be of great value in later applications of structural principles to practical problems. The various cases illustrated in following pages exemplify a type of problem which has been solved on the basis of the underlying principle of tensional rupture expressed in Dr. Mead's unpublished report of October 1937.

APPLICATION OF STRUCTURAL PRINCIPLES TO MINING PROBLEMS.

In determining the type of vein structure with which one is dealing, it is helpful to know something about the fracturing of the wall rock which adjoins the vein. Crosscuts and counterdrives sometimes reveal the type of pre-mineral fracturing more definitely than initial development headings driven on the vein. Once the vein structure is understood, exploration for branch veins and splits can be planned intelligently and economically. Many of these veins are mined by the cut and fill method, which requires a dependable supply of waste for filling mined sections as stoping advances. At times the waste can be obtained from some active exploration face, but frequently it is necessary to obtain it from crosscuts driven from stopes. The geologists and operators cooperate in determining advantageous locations from which these crosscuts can be driven, and productive branch veins are often found in this manner.

Recognition of the vein structure as having been caused by the normal fault type of rupture has been of considerable practical importance in the following cases.

Case I.

This vein strikes northwest and dips about 65 degrees northeast. Early in the course of development it was indicated that hangingwall and footwall branches of steep dip and parallel strike were likely to exist, and as stoping got under way, and proceeded upward, the possibility of finding ore on these branch fractures was kept in mind. Figure 2, a typical cross section, shows how these branches conform to the pattern of tension fractures formed during pre-mineral normal faulting. A short footwall crosscut gave the first actual evidence of the existence of an ore-bearing, branch vein. Where exposed in the crosscut, this split was only a narrow, low-grade stringer. Thinking that the stringer might prove to be an important footwall branch, short crosscuts were driven to it from higher stoping levels, where it was found to be productive. After yielding an appreciable tonnage, this footwall branch joined the main vein at a vertical distance of 30 meters above the point where it was first exposed.

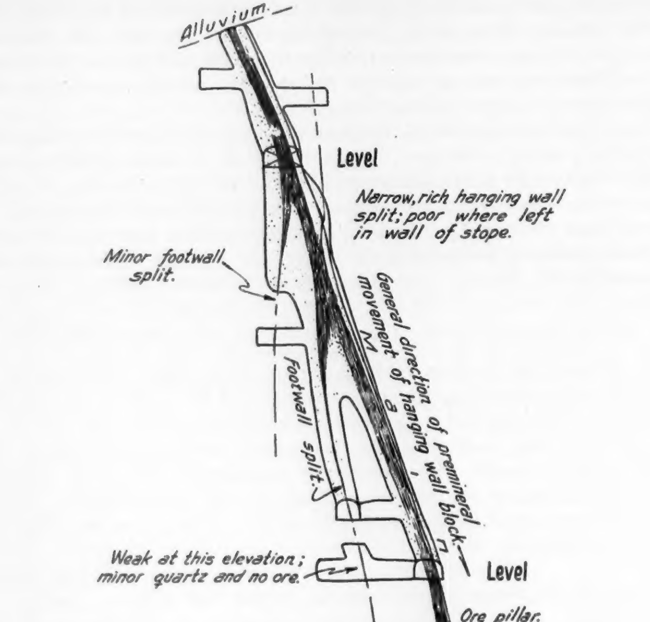


Fig. 2 - Cross section through vein discussed in Case I.

Case II.

This vein strikes approximately N 60° W and dips 75 degrees southwest. There are local variations in both strike and dip, but the irregularities which are most strikingly identified with the localization of ore are those of dip. Here again the fracture pattern is characterized by steeply dipping hanging-wall and footwall splits which are typical of tension cracks formed during normal faulting. The recognition of this structural condition has aided materially in planning exploration and development within the vein zone, and the interpretation of the fracture pattern has been applied in a sufficient num-

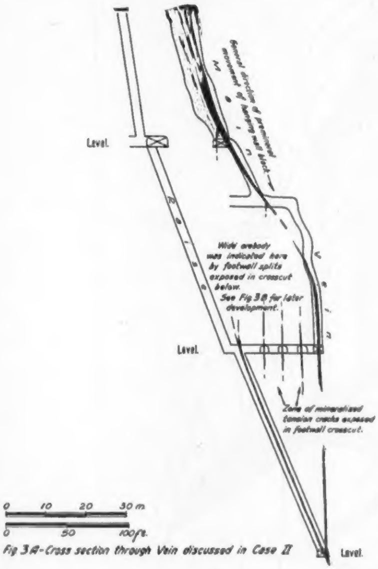


Fig 3A - Cross section through Vein discussed in Case II

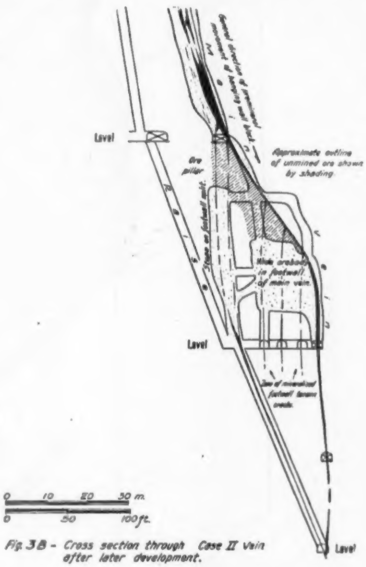


Fig. 3B - Cross section through Case II Vein after later development.

ber of cases to give the operators a fairly dependable rule of thumb in dealing with problems involving stringers adjacent to the main vein. Taking a centrally located section as a typical example, a cross section made at an early stage of development showed the picture given in Figure 3A. It was quite evident that the steep quartz stringers in the central part of the vein zone were mineralized footwall tension cracks. These carry spotty, non-commercial ore where first exposed by a footwall crosscut. Suspecting that this zone of footwall stringers would become wider and more intensely mineralized above the level, the operators were advised to keep in mind the possibility of a widening zone of ore in this section. In some parts of this vein the ore looks like ordinary moderately chloritized andesite, and the operators are frequently confronted with the problem of determining their ore limits, so any advice of this sort is helpful to them. The anticipated enlargement of the orebody later became a reality. Then the following problem arose: If this unusual increase in stoping width were to be a permanent condition, it would be necessary to change the system of stoping from cut and fill to square-

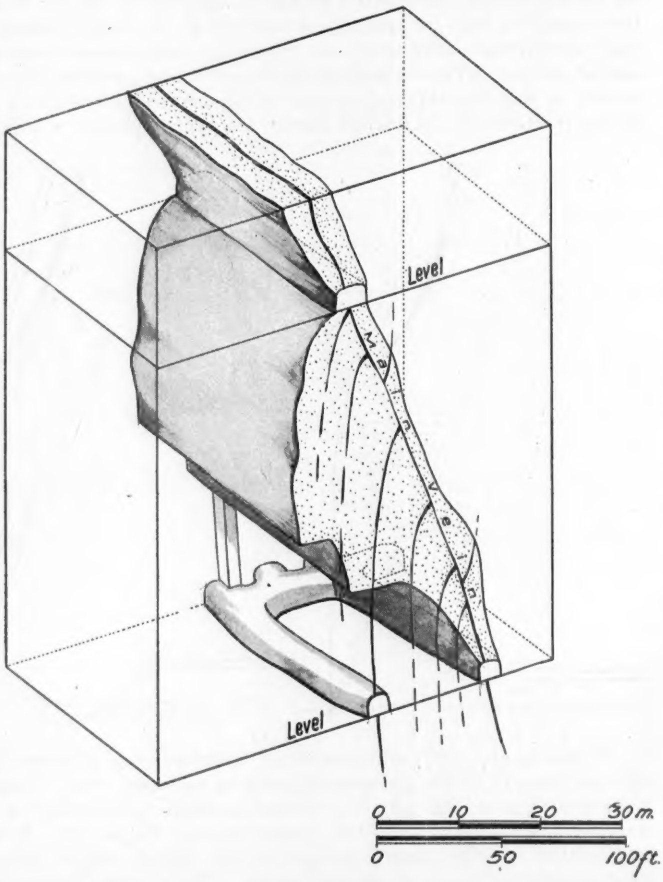


Fig. 4 - Isometric projection of part of vein discussed under Case II adjacent to the section shown in Figs. 3A and 3B.

set panelling; but, if it were only an erratic increase which would not be maintained for an appreciable vertical distance, it would be a mistake to change the stoping system. The fracture pattern, as suggested by the cross section shown in Figure 3A, indicated that a wide zone of ore would persist upward until the zone of footwall splits joined the main vein, a vertical distance which could be fairly well determined by geological data. The structural picture made it possible to foresee the condition with some degree of confidence, so

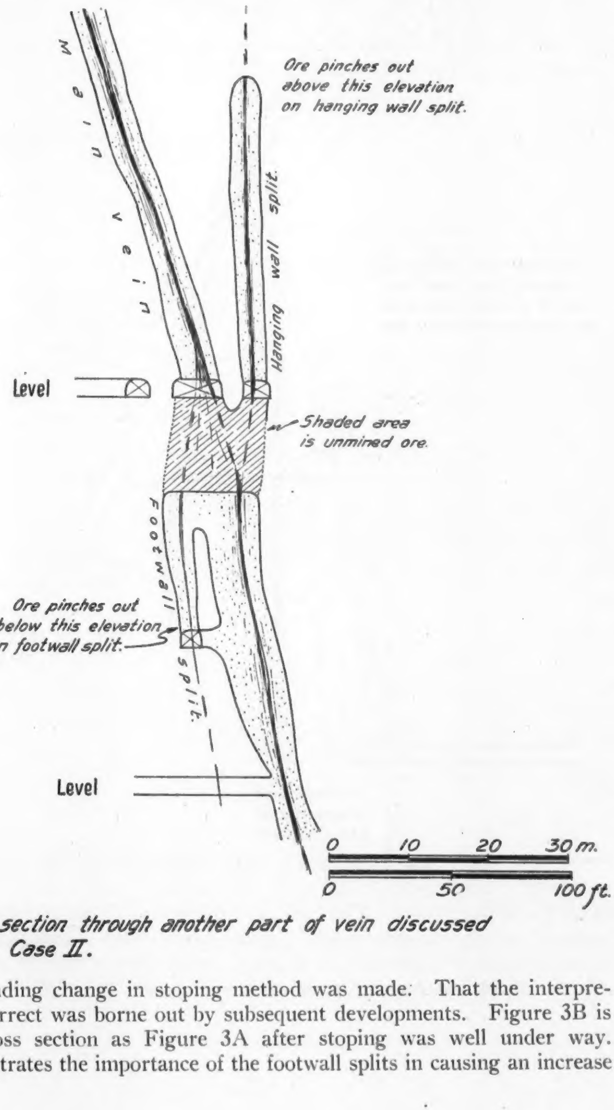


Fig. 5 - Cross section through another part of vein discussed under Case II.

the corresponding change in stoping method was made. That the interpretation was correct was borne out by subsequent developments. Figure 3B is the same cross section as Figure 3A after stoping was well under way. Figure 4 illustrates the importance of the footwall splits in causing an increase

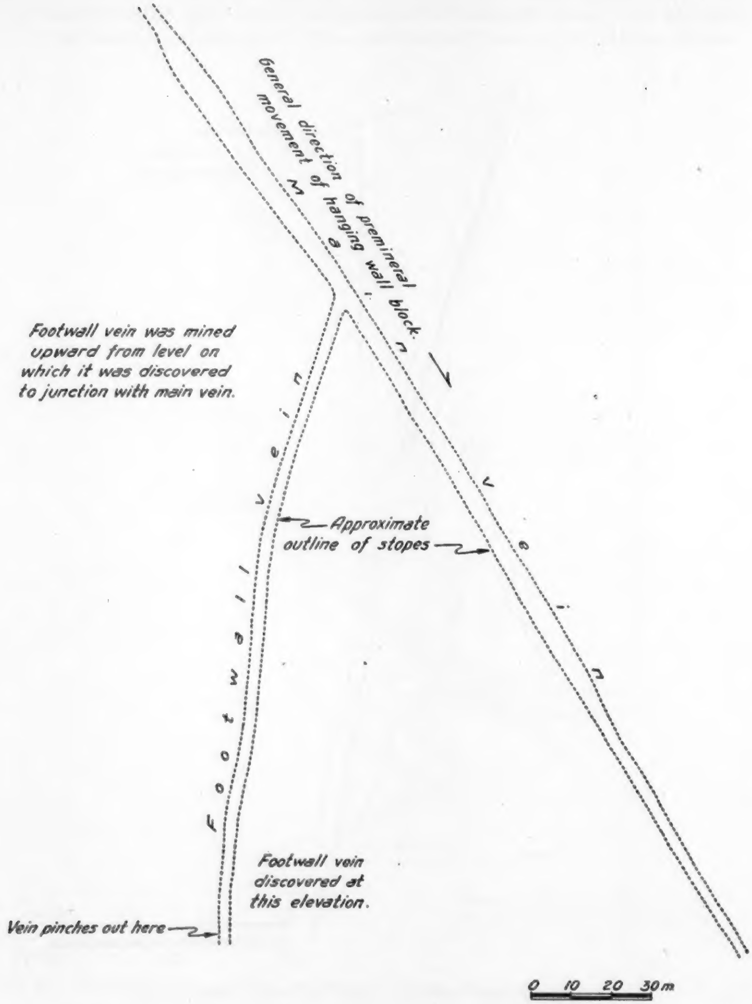


Fig. 6 - Cross section of vein discussed under Case III.

in vein width in another section of the same vein east of that shown in Figures 3A and 3B. Figure 5 shows stoping on a steeply dipping hangingwall split which is parallel to the main vein.

Case III.

This is a long vein which was an important producer of former years. It strikes easterly to northeasterly and dips southerly. Beyond its northeastern

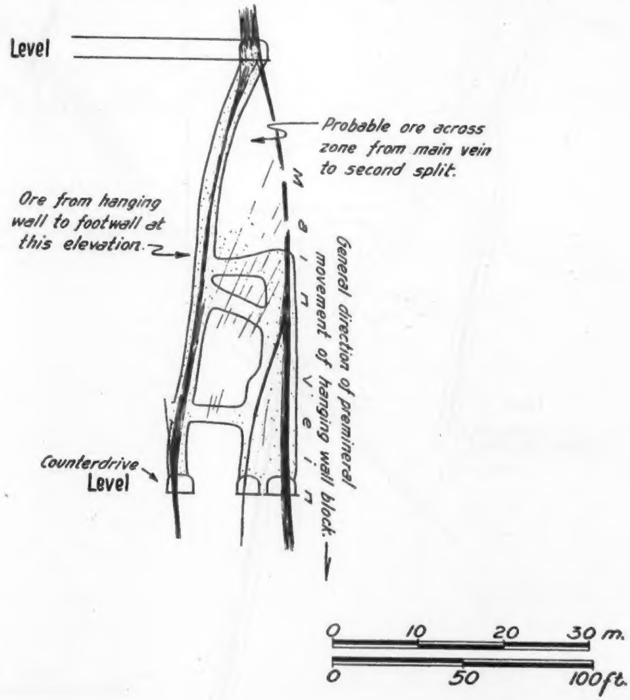


Fig. 7 – Cross section through vein discussed under Case IV.

limit of mineralization its prolongation is marked by a late fault along which there has been some horizontal movement. Pre-mineral fracturing, however, was evidently normal and tensional. One of the features which substantiates this is illustrated in Figure 6. The branch vein was found long after the main vein was worked out, being first exposed near its lower extremity where ore occurred in spotty and discontinuous lenses. In this case it was desirable to have some basis for determining the tonnage possibilities involved at the earliest possible date, but an ore reserve estimate based on conventional methods of cubication could show only small positive and probable tonnages. The geological picture pointed out that this was a footwall tension split which would eventually join the main vein at a higher elevation, in which case the ore should persist upward to this supposed junction. This seemed to justify a relatively liberal estimate of probable ore, which proved to be fairly close

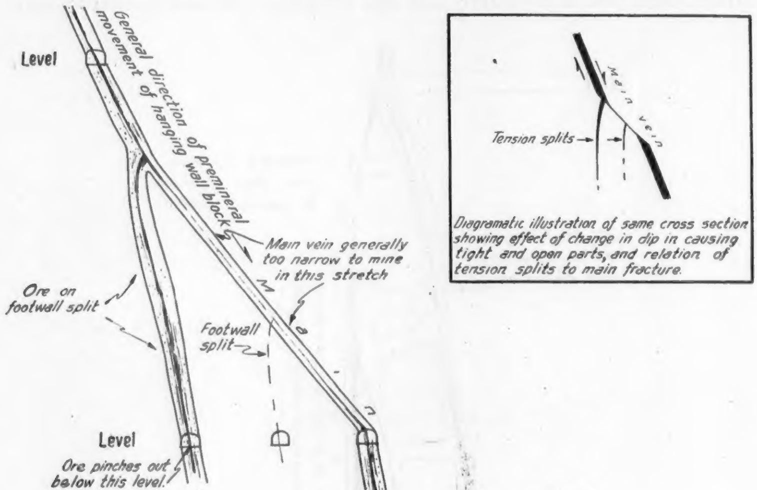


Fig. 8- Cross section through vein discussed under Case V.

about two years later when this footwall split was finally worked out to its junction with the main vein. An interesting feature in this case is the magnitude of the footwall split. At its lower extremity it lies about 75 meters in the footwall of the main vein, and from this point to its junction with the

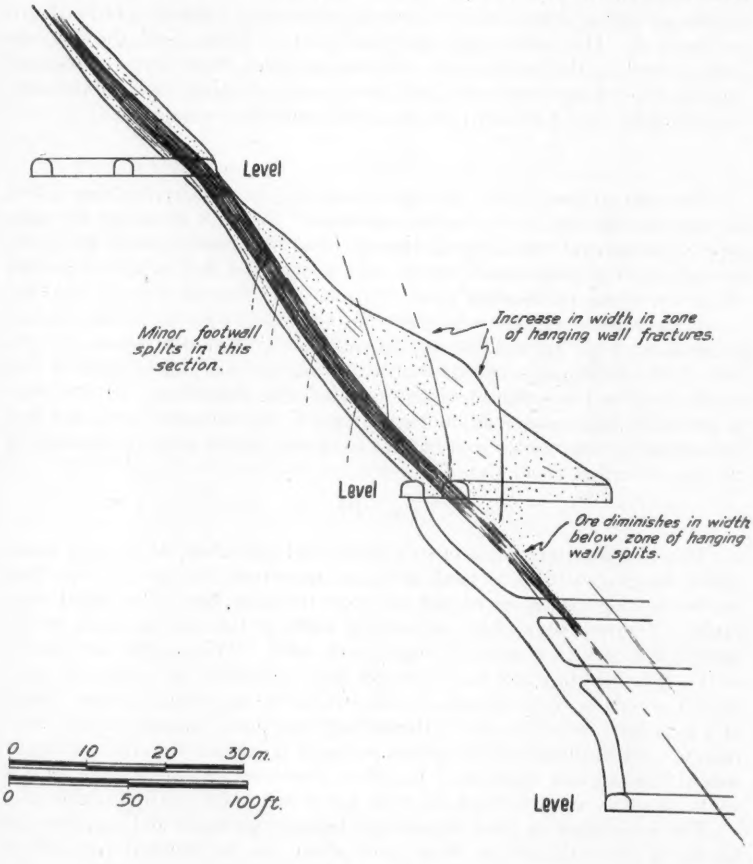


Fig. 9 - Cross section through vein discussed under Case VI.

main vein the vertical distance is about 150 meters. Considerable ore has been mined from hangingwall as well as footwall branches of this vein, these branch veins being roughly parallel to the main vein in strike but of much steeper dip, conforming in general to the idealized illustration in Figure 1.

Case IV.

While driving easterly and exploring this vein on a main level, some ore-bearing tension splits were observed which suggested that there might be additional splits of this type to be considered in the course of stoping. Later a footwall counterdrive exposed a second ore-bearing footwall split as shown in Figure 7. The second split was raised on to a higher level, the first one being mined in the main stope. Midway between these levels a footwall crosscut showed numerous splits, sufficiently mineralized to make ore throughout the entire stretch between the main stope and the second split.

Case V.

This vein strikes N 15° E and dips about 65 degrees easterly, being one of the outstanding veins of the north-south class. Figure 8 illustrates the same type of pre-mineral fracturing as that described in connection with the previous cases, being given mainly to show an example of this structural pattern on a vein of the north-south class. In this immediate locality the vein becomes too narrow to mine where the dip decreases, whereas in the Case II illustration (Figs. 3A and 3B) the decrease in dip is marked by a wide orebody. The explanation of this contrast is that the footwall in Case II was locally subjected to relatively intense pre-mineral shattering. In the characteristically tight ground adjoining the Case V vein, tensional splits are well defined and of appreciable size, but not so closely spaced as in the footwall of the vein described under Case II.

Case VI.

This comparatively flat vein strikes east and dips about 45 degrees south. Minor hangingwall and footwall splits are numerous, but not all those that are ore-bearing extend far enough out from the main vein to be mined separately. Figure 9 shows how the stoping width of the vein increases on the hangingwall side in a zone of hangingwall splits. These splits are parallel to the main vein in strike but of steeper dip. Obviously no geological guidance is needed in such instances as this, where the increment consists simply of a local increase in the size of the orebody and not a separate branch vein; however, the illustration is of interest in that it points out the effect of closely spaced hangingwall fractures. Excellent examples of ore-bearing tension splits, mined as separate veins, are to be found well in the footwall of this vein.

The importance of close cooperation between geologist and operator can hardly be overestimated in those cases where the ore extends outward on branch fractures for appreciable distances from the main vein. The illustrations given here are somewhat simplified and it may appear that the ore-bearing splits eventually would be found in the course of mining without any geological advice. This might be so in some cases, but the important fact is that unless the associated branches are discovered early enough to be mined while the main vein is being mined they might have to be left as unprofitable because of "heaviness" of the ground adjoining stoped sections. In addition to keeping in mind the time element involved as regards the mining of the footwall and hangingwall branches, the geologist must be aware of the effect of any late faulting which might obscure the junction of important ore-bearing splits with the main vein.

The foregoing illustrations might unduly tend to emphasize the importance of footwall fractures over the corresponding hangingwall splits, but if it were feasible to calculate the production from all individual branch veins, it is probable that the figures would show that the tonnage yielded from the footwall splits has been greater than that produced from the hangingwall counterparts.

In exploration work veins are often followed into ground where they become weak, ill defined, and hard to recognize. Under such conditions headings are driven on a pre-determined bearing and crosscuts or diamond drill holes are run at certain intervals to locate the main fracture. After a drive has been advanced on a definite line for some distance beyond where the vein was lost, there is often a question as to whether the main fracture is on the right or left side of the drive. As shown in Figure 1, the footwall and hangingwall tension cracks tend to be slightly concave toward the main fracture, and interpretations based on this feature have been successfully made in a number of instances in determining the position of the drive with respect to the main fracture. Though less practical than the applications explained in the foregoing cases, this serves to illustrate one of the various additional uses of a knowledge of the structural pattern.

Pachuca, Hgo., Mexico,
March, 1945.

SILLIMANITE IN SOUTH CAROLINA.

LAURENCE L. SMITH.

ABSTRACT.

Sillimanite has been found throughout a long belt in the Piedmont of South Carolina and Georgia. The host rock is a quartz mica schist, which presumably was originally an arenaceous sediment containing considerable aluminum. Sillimanite has been formed from biotite by the action of granite intrusions. Some deposits show promise of commercial value.

INTRODUCTION.

WHILE mapping soils in Spartanburg County, South Carolina in 1937, D. Hoye Eargle, geologist with the U. S. Soil Conservation Service, noted that a distinctive soil type was produced by a particular schist. Miss Glass of the U. S. Geological Survey examined this schist in 1942 and found that it contained sillimanite. The writer confirmed this identification early in 1943 and found numerous additional occurrences of sillimanite-rich schist in Greenville County southwest of the original discoveries.[1]

Subsequently, W. C. Hudson [2, 3] of the U. S. Bureau of Mines has mapped over 150 exposures of sillimanite-bearing rock in a belt extending from near Spartanburg, South Carolina, southwestward to the vicinity of Talbotton, Georgia, a distance of about 250 miles. This paper is based upon studies of deposits found between the Saluda and North Tyger rivers in Spartanburg and Greenville counties, South Carolina. Some of these deposits offer promise of being commercially workable.

GENERAL GEOLOGY.

The geology is, in general, comparable to most of the southern Piedmont. Similar formations occur to the northeast in the Gaffney-Kings Mountain area which has been mapped and described by Keith and Sterrett.[4]

Gneisses and schists of both igneous and sedimentary origin, together with granite intrusives, are the principal rock types, all of which have been intruded by granite pegmatites, quartz veins, and basic dikes.

Schistosity of the metamorphics, flow structures in the granites, and minor folds in the schist generally have northeast trends, although locally they may exhibit northwest directions. A striking example of northwest trends occurs in Paris Mountain, a conspicuous ridge near Greenville, whose direction

[1] Smith, L. L.: Sillimanite in South Carolina. Eng. & Min. Jour., vol. 144, Aug. 1943, p. 75.

[2] Hudson, W. C.: Personal communication.

[3] Hudson, W. C.: Sillimanite find in South proves important. Eng. & Min. Jour., vol. 145, Sept. 1944, p. 81.

[4] Keith, Arthur, and Sterrett, Douglas B.: Gaffney-Kings Mountain Folio, South Carolina—North Carolina. U. S. Geol. Surv. Atlas No. 222, 1931.

conforms to that of the schist and numerous included concordant dikes which compose it.

Deep residual soils make it difficult to accurately map contacts and to obtain fresh specimens for microscopic study.

Only the rocks with which the sillimanite is associated are described in this paper. These are mica schist, granite, pegmatites, and derivatives of the latter.

MICA SCHIST.

The host rock for the sillimanite is a quartz mica schist. This is presumably a phase of the pre-Cambrian Carolina gneiss of Keith, the most widespread formation of the southern Piedmont. Quartz, biotite, muscovite, and magnetite are generally its sole constituents. The proportions of the micas vary consideraby. Locally, muscovite is partly supplanted by sericite, and chlorite replaces biotite. Sillimanite becomes abundant near granite contacts where also a little garnet may be found. Secondary limonite is abundant throughout the zone of weathering.

The schist is uniformly fine to medium grained. It has a pronounced schistosity resulting from parallel orientation of the mica plates and sillimanite prisms. Also, much of the quartz is distinctly elongated. Some mica has developed with its cleavage normal to the schistosity and much of the sillimanite has random arrangements. There is only a slight tendency toward segregation of quartz and mica. A distinct gneissoid structure, however, is developed where the rock is intimately intruded by thin veins of pegmatite.

In places the more micaceous phases of the schist are plicated (Fig. 1). This structure is found near granite bodies and is believed to be due to pressures exerted by intrusion.

The schist is believed to have been formed by regional metamorphism from a shale or grit which was high in silica and contained considerable aluminum. No traces of bedding are discernible, possibly because of obliteration by metamorphism. Certain zones composed largely of mica and others predominately of quartz, may represent primary differences in the original materials, the micaceous having formed from the more clayey and the quartzose from the more sandy layers.

GRANITE.

Most granites in this section of the Piedmont are gray, medium-grained rocks which vary in structure from generally massive to highly schistose near the borders of intrusions.

A specimen from Piney Mountain near Greenville carries quartz, microcline, orthoclase, oligoclase, biotite, and muscovite as essential minerals, named in order of their abundance. The common accessories are apatite, zircon, and magnetite. This composition is similar to Keith's Whiteside Granite,[5] which he has tentatively classified as Carboniferous. Megascopic examination indicates that all the sillimanite is associated with granite closely resembling Keith's prototype.

[5] Op. cit., p. 6.

Some granite intrusions are batholiths or dikes with dimensions of several miles. Smaller dikes ranging in width from a few feet to mere seams are commonly abundant near the borders of the large intrusions. Many large masses of schist are roof pendants enclosed within large dikes or stocks. Most of these masses are invaded by numerous small dikes. Probably no large area of schist in this locality is free from intrusions of various types and sizes.

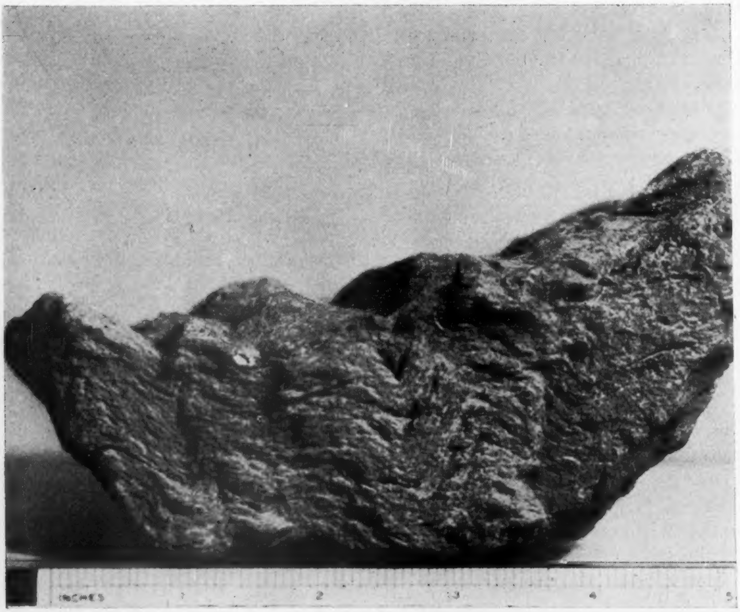


FIG. 1. Plicated sillimanite schist from Greenville Co., S. C.

Although the majority of the smaller dikes are concordant with the schistosity, a few follow joints in the schist. The large intrusions generally have concordant contacts but some cross-cutting occurs. Many roof pendants are synclines with the schistosity paralleling the bordering granite. Most contacts are sharply defined although locally, along the borders of the large intrusions, some assimilation of the schist has taken place.

PEGMATITES AND QUARTZ VEINS.

Granites and schists are cut by pegmatite dikes, some of which grade into quartz veins. These, like the granite dikes, generally conform to the schistosity but follow joints where they are pronounced. Some pegmatites are five to fifteen feet thick, but the great majority are only inches or fractions of an inch in thickness. Near large granite bodies the schist is, in places, intimately injected by these pegmatites and quartz veins forming migmatite with a conspicuous gneissic structure. The layers of intervening schist show no evidence of alteration by the veins. Sillimanite where present in the migmatite is always confined to the leaves of original schist.

SILLIMANITE.

Occurrence and Distribution. Sillimanite is confined to the schist near granite contacts. The richest and largest deposits are in roof pendants or adjacent to the largest intrusions, while leaner deposits are found near smaller dikes. Since sillimanite does not occur in pegmatite, the tenor of the injection gneiss is much lower.

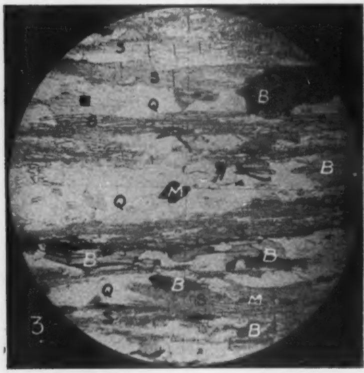
FIG. 2. Weathered surface of schist showing sillimanite with random orientation.

Rich sillimanite-bearing schist has been found as far as two hundred feet from granite contacts. Because of poor exposures, the maximum limits of mineralization have not been determined. In places where sillimanite appeared far removed from igneous masses, further examination indicated that the schist was a roof pendant with underlying granite at no great depth.

There is much variation in amount of sillimanite within the schist, preference being shown for the zones richer in biotite mica. The content of twenty samples from various exposures ranges from three to thirty per cent.

[6] Hudson, W. C.: Personal communication.

Mineralogy and Paragenesis. Sillimanite occurs as long colorless prisms and needles, most of which range from 1 to 6 mm. in length. Groups of conspicuously smaller crystals, ¼ to 1 mm. long, constitute a portion or even all the sillimanite in places. Exceptionally large prisms are 12 mm. long and 2 mm. in width (Fig. 2). Most of the larger crystals parallel the schistosity but random orientations are common. The smaller crystals occur in clusters forming felt-like bunches intergrown with biotite (Fig. 3). Long lenticles or blades consisting of a number of needles are abundant in places and these greatly accentuate the schistosity (Fig. 4). Sericite is commonly intimately



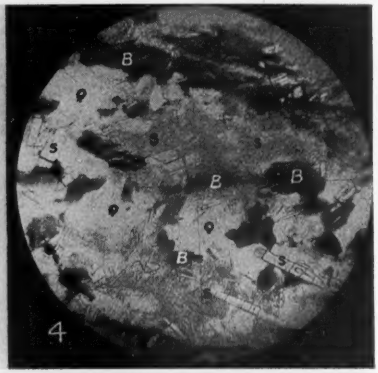


FIG. 3. Photomicrograph of sillimanite schist from Spartanburg County, South Carolina. Sillimanite (S) in needles and lenticles. Biotite (B). Quartz (Q). Magnetite (M), the small crystals near bottom are secondary after biotite. Long black irregular streak is limonite. × 35.

FIG. 4. Photomicrograph of sillimanite from Spartanburg County, South Carolina. Biotite (B) altering to felty bunches of minute sillimanite crystals (S). Larger sillimanite prisms cutting quartz (Q). × 35.

associated with sillimanite in the lenticles, the sharp frayed ends of both minerals being so intergrown and overlapping as to superficially give the appearance of a single crystal. Billings[7] describes similar intergrowths occurring in schists in New Hampshire.

In the plicated schist the sillimanite prisms are generally bent in perfect conformity with the minute folds. Occasional crystals exhibit slight fracturing and a few intersect the foliation.

Quartz, biotite, muscovite, and most of the magnetite are primary with respect to the schist. Chlorite and some magnetite are secondary after biotite. Sericite is formed in part from the alteration of biotite and probably in part from recrystallization of muscovite.

Sillimanite is the principal secondary mineral and intersects all others except chlorite.

[7] Billings, Marland P.: Structure and metamorphism in the Mount Washington area, New Hampshire. G. S. A. Bull., vol. 52, 889, 1941.

Origin of Sillimanite. Sillimanite has resulted from contact metamorphism of a schist by granite intrusions. This is suggested by its distribution, invariably near the intrusions, and by a microscopic study of the schist. Biotite has altered into sillimanite, magnetite, and sericite. Chlorite is also secondary after biotite but is presumably of later origin. Probably some sillimanite has formed from muscovite, but the evidence for this is less clear. The sheaves of small crystals, intergrown with biotite, have formed in place (Fig. 3). The larger crystals, which parallel the foliation or intersect quartz and occur some distance from the parent mica, have grown by diffusion of the constituents through the rock.

There is no evidence that any new constituents have been added to the schist by igneous metamorphism. The sillimanite has apparently been developed solely by the agents of heat and aqueous solutions.

Absence of sillimanite in pegmatite veinlets and abundance in intervening leaves of schist indicate that crystallization of sillimanite took place prior to the intrusion of pegmatite. If the plication of the schist is correctly deduced as being contemporaneous with the intrusion of the granite bodies, then the growth of sillimanite crystals is likewise simultaneous with this early igneous stage. This is indicated by the bending of crystals in conformity with the contorted schist. The few fractured crystals and others intersecting the plications suggest that crystallization overlapped the period of folding.

The following sequence of events is deduced:

1. Regional metamorphism of aluminous sediments converting them into quartz mica schists.
2. A period of granitic intrusion.
3. Development of sillimanite from micas during an early stage of igneous activity.
4. Intrusion of pegmatite and quartz veins.

Kyanite appears to have developed at a lower temperature than sillimanite. Stuckey[8] concludes that the kyanites of North Carolina were formed by ". . . residual solutions accompanying pegmatite formation. . . . as one of a series of pegmatite replacements . . .," or ". . . by metasomatic replacement . . . by solutions given off by pegmatite dikes. . . ." The conspicuous absence of sillimanite in pegmatite indicates that it formed in an earlier stage of intrusion, and probably at higher temperatures than kyanite.

Comparison with New Hampshire Deposits. Marland P. Billings[9] and Katharine Fowler-Billings[10] have described sillimanite in New Hampshire with many features similar to those possessed by the South Carolina deposits. Chief among such common features are: (1) the host rocks are mica schists; (2) the schists have been subjected to igneous metamorphism; (3) sillimanite and muscovite or sericite are commonly intimately intergrown forming long lenticles or bundles; (4) the percentages of sillimanite are comparable; and (5) the deposits occur in the form of long narrow belts.

[8] Stuckey, J. L.: Cyanite deposits of North Carolina. Econ. Geol., vol. 27, p. 673, 1932.

[9] Op. cit.

[10] Billings, Katharine Fowler: Sillimanite deposits in the Monadnock quadrangle, New Hampshire. N. H. State Planning and Development Comm. Part 8, 1944.

The New Hampshire sillimanite differs from that of South Carolina in these respects: (1) much of it is associated with andalusite, staurolite, or tourmaline; (2) the crystals are much larger, some being 25 mm. long as compared with maximum lengths of 12 mm. in South Carolina; (3) it contains magnetite inclusions while that in South Carolina is readily separated from all associated minerals; and (4) the New Hampshire sillimanite shows alteration to sericite.

According to Billings,[11] andalusite and staurolite schists are formed from more aluminous clays while the mica schists have developed from arenaceous sediments. Probably all the South Carolina source materials were deposited under warm climatic conditions and sandy sediments resulted. Thus regional metamorphism produced extensive comparatively uniform quartz mica schists. The presence of tourmaline, greater amounts of garnet, larger crystals, and sericitization of the sillimanite may be explained by the more complex igneous metamorphism to which the schists in New Hampshire were subjected.

University of South Carolina,
Columbia, South Carolina,
Feb. 19, 1945.

[11] Billings, Marland P.: Idem, p. 887.

REVIEWS*

The Geology of Missouri. By E. B. BRANSON, Professor of Geology, University of Missouri, plus a Board of Editors. Pp. 535; Figs. 51; Pls. 49. University of Missouri, Columbia, Mo. Price, $3.00.

"The Geology of Missouri," by E. B. Branson, University of Missouri Studies, Volume 19, No. 3, 1944, is an exhaustive compilation of the works by numerous students of the geology of Missouri. It contains 49 plates and 51 figures representing stratigraphic sections, maps and plates of fossils, all very well illustrated.

The section on the economic geology, though treated only briefly, is very well presented. It gives the reader a general over-all picture of the economic resources and their distribution in Missouri.

Probably one of the most outstanding contributions of the publication is the bibliography. This should prove very useful to those concerned with a more detailed study of the various phases of the geology of Missouri. The bibliography does not, however, include the recent work of James S. Cullison, "The Stratigraphy of Some Lower Ordovician Formations of the Ozark Uplift," University of Missouri School of Mines and Metallurgy, volume 15, No. 2, June 1944.

In summary I would say that the "Geology of Missouri," by Dr. Branson, is an important contribution, and should prove invaluable to those students interested in any phase of geology of that great state.

WILLIAM R. HORNEY.

BOOKS RECEIVED.

RALPH E. DIGMAN.

Geology and Manganese Deposits of Northeastern Tennessee. PHILIP B. KING, H. W. FERGUSON, L. C. CRAIG AND JOHN RODGERS. Pp. 275; Figs. 35; Pls. 8; Tables 30. Bull. 52, Tenn. Division of Geology, Nashville, 1944. *A thorough account of the manganese deposits of northeastern Tennessee including the area of Bumpass Cove. The regional geology, stratigraphy, structure and land forms of the area are described. The occurrence of the oxidized ore in the Lower Cambrian Shady dolomite is fully discussed. Eight sheets of maps and sections are included in pockets.*

Manganese and Quartzite Deposits in the Lick Mountain District, Wythe County, Virginia. F. W. STEAD AND G. W. STOSE. Pp. 16; Figs. 3; Pls. 8; Tables 3. Bull. 59, Virginia Geological Survey, University, 1943.

Review of Petroleum Geology in 1944. F. M. VAN TUYL, W. S. LEVINGS AND OTHERS. Pp. 136; Figs. 4; Pls. 4. Vol. 40, No. 2, Quarterly of the Colorado School of Mines, Golden, 1945. Price, $1.00. *An important and complete review of developments in petroleum geology and allied subjects in the past year. Scientific contributions, publications, and noteworthy discoveries affecting the petroleum industry are discussed. Production and reserve figures are given. A 35-page bibliography of the year's important publications is appended.*

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

Illinois Mineral Industry in 1943. W. H. VOSKUIL AND D. F. STEVENS. Pp. 89; Figs. 12; Tables 65. Report of Investigations, No. 101, Illinois Geological Survey, Urbana, 1944.

Biennial Report, 1943–1944. GARLAND PEYTON. Pp. 43; Figs. 11. Georgia Geological Survey, Atlanta, 1945.

Bureau of Mines, Washington, 1945.

Differential Thermal Analysis, Its Application to Clays and Other Aluminous Minerals. SIDNEY SPEIL AND OTHERS. Pp. 81; Figs. 35. Tech. Paper 664. Price, 25 cents.

Analysis of Tennessee Coals (Including Georgia). A. C. FIELDNER AND OTHERS. Pp. 243; Figs. 3. Tech. Paper 671.

Energy Requirements and Equilibria in the Dehydration, Hydrolysis, and Decomposition of Magnesium Chloride. K. K. KELLEY. Pp. 26; Figs. 9. Tech. Paper 676. Price, 10 cents.

Accidents from Hoisting and Haulage in Metal Mines. Metal-Mine Accident-Prevention Course, Section 3. Pp. 60; Figs. 30; Tables 5. Miners' Circular 53. Price, 15 cents.

Ontario Department of Mines, Toronto, 1945.

Geology and Mineral Deposits of the Red Lake Area. H. C. HORWOOD. Pp. 231; Figs. 103; Pls. 13; Tables 8. Vol. XLIX, Pt. 2, 49th Annual Report.

Geology of the Whitefish Bay Area, Lake of the Woods. N. H. C. FRASER. Pp. 19; Fig. 1; Pl. 1. Vol. LII, Pt. 4, 52nd Annual Report.

Mineral Occurrences in the Renfrew Area. J. SATTERLY. Pp. 138; Figs. 17; Pls. 2. Vol. LIII, Pt. 3, 53rd Annual Report.

A Faixa Estanifera do Rio Grande do Sul. R. R. FRANCO. Pp. 54; Figs. 41; Pl. 1. Mineralogia, No. 6, Boletim XLIV, Universidade de São Paulo, S. Paulo, Brazil, 1944.

Paleontologia Estratigrafica de los Sedimentos Neógenos de la Provincia de Córdoba. A. CASTELLANOS. Pp. 46. Publicaciones No. 23, Instituto de Fisiografia y Geologia, Rosario, Argentina, 1944.

The Dept. of Publications, Colorado School of Mines at Golden announces that the publication, **Geophysics in War,** *by* C. A. HEILAND, *Vol. 37, No. 1 of the* **Quarterly** *is again available for distribution. The number, published in January 1942, has been withheld from circulation at the request of the Office of Censorship.* Price, $1.00.

The U. S. Geological Survey, in cooperation with 12 oil companies, has published a tabular listing of all wells drilled for oil and gas in Wyoming. The compilation includes locations, counties, fields, well numbers, operators' names, elevations, surface and bottom-hole geologic formations, names and depths of producing formations, total depths, and present status of some 8,000 wells. A limited number of the well lists will be available for free distribution to land owners, lessees, oil companies, and others whose activities aid in the discovery and development of the oil and gas resources of Wyoming.

SOCIETY OF ECONOMIC GEOLOGISTS

ARTHUR FRANCIS DUGGLEBY

1893–1945

Arthur Francis Duggleby was born of English parents at Brisbane, Australia, but was brought up and educated in the United States, first in the public schools at Davenport, Iowa, and later at the Colorado School of Mines at Golden. He was a mining geologist of marked ability and a brilliant mining executive. His professional work took him to Cuba, South Africa, various parts of the United States and finally to the Philippines, where he met his death. In World War I he served in the famous 27th Engineer regiment and later was for some years a member of the field staff of Newmont Corporation. It was that organization which sent him to the Philippines.

On completion of his commission with the Newmont Corporation Duggleby resigned to join the staff of the Benguet Consolidated Mines where he promptly became Manager and, soon after, Operating Vice President. The Benguet mine, one of the largest properties in the Philippines, was supposed to have been bottomed and indeed the company had started to liquidate. Duggleby brought to the organization not only great energy and exceptional ability but a fine understanding of ore deposits. He reoriented the development work and soon made it a great gold mine. In succession and for the same company he developed the neighboring Balatoc gold mine, the Florannie high grade metallurgical chromite deposit, and the really great Masinloc deposits of refractory chromite ore. Thus he rapidly became one of the recognized leaders of the mining profession in the Philippines and had an important part in pushing gold production up to where it exceeded that of every American state but California.

Duggleby also led in many public movements and became widely known as a sound counsellor and hard working executive. It was inevitable, when the Japanese put the nationals of America, Great Britain and other United Nations into internment camps, that Duggleby should become Vice Chairman of the Executive Committee of internees at Santo Tomas, the largest camp. Here for three long years he worked devotedly and ably for the welfare of the inmates, without sparing himself and, seemingly, without the least consideration of any personal danger. To him and his associates the internees owe an unrepayable debt. On December 23, 1944, Duggleby and three others on this committee were arrested by the Japanese military police and put in the camp jail. On January 5 they were taken away and their fate was unknown until some time after the recovery of Manila by Philippine and United States troops. On February 25 their remains and those of a number of others were found buried in a shallow trench in a vacant lot. No public statement has been made of the charges against them, a procedure not uncommon in Manila during Japanese occupation. Presumably they were shot as "noncollaborators." If so they were gloriously guilty, to their great credit and the honor of our profession.

H. Foster Bain.

SCIENTIFIC NOTES AND NEWS

HORACE FRASER, Assistant Chief, Metals Division, F.E.A., has left for a brief trip to London in connection with negotiations on Turkish-Chrome.

ROBERT BUTLER, Chief of the Quartz Program in Brazil for the F.E.A., has been in Washington for conferences and has returned to Brazil.

WILLIAM D. JOHNSTON, JR., on the F.E.A. staff in Brazil, was in Washington for two weeks and has now returned to Brazil.

ALAN M. BATEMAN addressed the Canadian Institute of Mining and Metallurgy in Quebec on the "Post-War Outlook for the Base Metals."

ANTON GRAY has left New York for a trip to the Western Kennecott properties.

RAYMOND BROOKS has left for extended professional work in South Africa.

QUENTIN SINGEWALD has returned to Washington from Colombia and Venezuela where for over two years he has been doing field work for the Metals and Minerals Divisions of the F.E.A.

WILLIAM FOSHAG will shortly return to the Smithsonian Institute after three years in cooperative field work for the U. S. Geological Survey and the Foreign Economic Administration in Mexico.

DEAN FRASCHE has gone to New Caledonia on professional business.

BENNETT BATES is returning to Washington from his post as Chief of the Minerals Staff of the F.E.A. in Australia and New Caledonia.

D. H. MCLAUGHLIN has returned to Peru for a brief trip.

ROBERT DONALD has returned to Washington from field examinations in British Guiana for the Metals and Minerals Divisions of the F.E.A.

IRA JORALEMON has returned from a professional trip to Bolivia.

PAUL BUNDY has completed his field work for the F.E.A. in Bolivia and is now in California.

WILLIAM SCHMIDT has been transferred from the Chile staff of the F.E.A. to the Washington staff where he will have charge of copper in the Metals Division.

LAWRENCE MCK. GOULD, professor of geology and geography at Carleton College for the past thirteen years, has been appointed president of Carleton with the opening of the coming college year.

H. G. FERGUSON has resumed field work in the West.

PROFESSOR IAN CAMPBELL is temporarily stationed at Seattle 4, Washington, where he is serving under the Commanding Officer, Fleet Operational Training Command, Room 1912, Exchange Building. A part of his time is devoted to special work with the Division of War Research, U. S. Navy Radio and Sound Laboratory, San Diego, California.

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